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"THE USE OF IMPULSE RADAR TECHNIQUES FOR DEPTH PROFILING OF PEAT DEPOSITS"

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ABSTRACT

With the growing interest in peat as an energy fuel, the need for better inventories of this resource becomes increasingly important. Although conventional imaging sensors can provide information on the areal extent of peatlands, depth measurements must still be taken in the field in order to estimate the volume of material present. A recently completed program conducted in eastern Newfoundland suggests that impulse radar systems can provide depth information and volume estimates comparable to those obtained with manual measurement techniques, in much less time and with considerably less effort. When used in a profiling mode, the impulse radar records provide a more detailed portrayal of the deposit bottom and indicate the presence of snags and internal interfaces within the peat.

Ground-based data was acquired in mid-summer and early fall using 80 MHz and 400 MHz radar systems towed behind an all-terrain vehicle. Airborne data was collected using an 80 MHz and a 120 MHz system mounted beneath a helicopter in summer, fall, and winter. In the case of ground-based profiles, peat thickness of up to 8.1 metres was clearly visible; no deeper deposits were situated within close proximity of the base of operations, which prevented determination of the maximum detectable depth. The airborne profile data was generally poorer in quality, and was limited by reflections from the peat surface. However, depths of up to 4.8 metres were successfully profiled from an altitude of 1.5 metres. Point soundings made when the helicopter was on the surface of the deposit yielded quite strong returns, and would presumably be as successful as ground-based measurements for deeper thicknesses of peat. No significant seasonal variations were observed.

Impulse radar techniques should be able to contribute to all levels of peat resource assessment. However, since they do not appear to provide any information on the quality of the peat material, they would seem to be particularly useful for reconnaissance level surveys. In most cases, the use of a single propagation velocity for all deposits would seem to be justified, but in some instances it may be necessary to determine the velocity at each site in order to minimize absolute errors. Although the technique can now be used operationally, further data collection would provide a better understanding of the variability of impulse radar propagation in peat. Additional research is needed in order to develop a system suitable for airborne profiling.

RESUME

Avec l'intérêt grandissant que suscite l'utilisation de la tourbe comme source d'énergie, la nécessité de mieux connaître nos ressources dans ce domaine se fait du plus en plus pressante. Bien que les techniques habituelles de détection par visualisation fournissent des renseignements sur l'étendue d'une tourbière, il faut encore, pour évaluer le volume de matière en présence, que l'on se rende sur le terrain pour y effectuer des mesures de profondeur. Les résultats d'une étude récemment terminée dans l'est de Terre-Neuve donnent à entendre que les systèmes de radar à impulsions permettent d'obtenir, beaucoup plus rapidement et avec beaucoup moins d'efforts, des renseignements sur la profondeur des tourbières et des estimations du volume de ces dernières qui sont comparables à ceux que donnent les techniques de mesure manuelles. Lorsqu'on l'utilise pour déterminer le profil du sol, le radar à impulsions fournit une image plus detaillée du fond du gisement et il indique la présence des inclusions et des interfaces à l'intérieur de la tourbière.

Les données enregistrées à partir du sol ont été obtenues au milieu de l'été et au début de l'automne à l'aide d'un système de radar de 80 MHz et 400 MHz remorqué par un véhicule tout terrain. Les données enregistrées à partir des airs ont été obtenues pendant l'été, l'automne et l'hiver à l'aide d'un système de radar de 80 MHz et 120 MHz monté sous un hélicoptère. Dans le cas des profils obtenus à partir du sol, on a enregistré clairement des profondeurs allant jusqu'à 8,1 mètres de tourbe. Comme il n'y avait pas de gisements plus profonds à proximité de la région où s'effectuaient les travaux la profondeur maximale de détection n'a pu être déterminée. La qualité des données obtenues à partir des airs était en général moins bonne et les résultats étaient limités par la réflexion à la surface de la tourbe. Toutefois, des profondeurs allant jusqu'à 4,8 mètres ont été déterminées avec succès à une altitude de 1,5 mètre. C'est la détection ponctuelle effectuée lorsque l'hélicoptère était au-dessus de la surface de la tourbière qui a donné les meilleurs résultats; il est permis de croire que cette méthode serait aussi efficace que les mesures effectuées à partir du sol pour des tourbières plus profondes. Aucune variation saisonnière d'importance n'a été constatée.

Les techniques fondées sur l'utilisation du radar à impulsions devraient pouvoir servir à tous les aspects de l'évaluation des ressources en tourbe. Cependant, comme ces techniques ne semblent pas fournir de renseignements sur la qualité de la tourbe, elles sembleraient plus indiquées pour la reconnaissance des gisements. Dans la plupart des cas, l'utilisation d'une vitesse de propagation unique pour tous les gisements semblerait justifiée; cependant, dans certains cas, il pourrait être nécessaire de déterminer la vitesse pour chaque gisement afin de minimiser les erreurs absolues. Bien que la technique soit déjà utilisable à l'heure actuelle, il serait bon d'obtenir d'autres données pour mieux comprendre la variabilité de la propagation des ondes de radar à impulsions dans la tourbe. D'autres recherches seront nécessaires pour mettre au point une méthode appropriée pour la détection aérienne.

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EXECUTIVE SUMMARY

I INTRODUCTION

With the growing interest in the development of Canada's peat reserves, the need for adequate inventories of this resource has become increasing important. Reconnaissance level surveys involve the mapping of peatland areas from aerial photographs or satellite imagery combined with a limited amount of field measurement of representative deposits. This level of assessment is usually more concerned with the estimating the total amount of peat present within a large region, rather than evaluating the quality of the material within specific deposits. The next level of inventory involves selection of deposits suitable for development. All deposits over a certain size within a local area may be field sampled, for both qualitative and quantitative information. Finally, in preparing a deposit for peat excavation, intensive grid sampling and surface elevation surveys are conducted in order to develop a drainage and mining plan.

The collection of depth information is critical at all levels of peat investigation. Traditionally, manual techniques have been used to measure peat thickness, which involves pushing metal rods down through the peat column. This is a time-consuming and hence a costly procedure, particularly where peatland areas are extensive or deposits are relatively deep. Impulse radar techniques have been used previously for a variety of subsurface profiling applications, from the measurement of coal thickness to the detection of oil under ice. In order to assess the utility of impulse radar for depth profiling of peat deposits, a study was carried out by Remotec Applications Inc. of St. John's, Newfoundland, under a contract awarded by the Renewable Energy Office of the National Research Council of Canada.

Field data was acquired for six peat deposits in eastern Newfoundland. This involved manual depth measurement and a limited amount of sample collection from surveyed points on each deposit. Impulse radar data was collected using both a ground-based and an airborne (helicopter) platform. Ground-based profiles were acquired with 80 MHz and 400 MHz antennae towed behind an all-terrain vehicle, during summer and fall field programs. Airborne data collection consisted of profiling as the deposits were overflown and point soundings taken with the helicopter set down on the surface. A 120 MHz radar system was used for most of the airborne measurements and was tested in summer, fall, and winter; some 80 MHz data was also collected during the fall program. A number of Wide Angle Reflection and Refraction measurements were undertaken in order to calculate the radar propagation velocity and the dielectric constant of peat. These were found to be unreliable, and an empirical approach was adopted to determine these parameters. In addition, one experiment was carried to estimate the attenuation of the radar signal with depth.

II CONCLUSIONS

Based on the operational experience gained during the field programs and the results of the data analyses, tentative answers can be given to the questions posed as the study objectives:

1) Q: Does impulse radar provide consistent and reliable measurements of peat thickness?

A: For 80 MHz ground-based data, the radar delay times were very consistent with the manually measured 'ground truth' depths within each deposit. Peat thicknesses of up to 8.1 metres were clearly visible. The confidence intervals associated with any given radar-predicted depth value were comparable with the estimated variability of single point manual measurements. It appears that the radar propagation velocity may be significantly different between some deposits, but a standard (composite) velocity can be used in most cases.

2) Q: Can impulse radar provide any additional information on the peat composition or deposit structure?

A: No correlation was found between the radar response and any of the parameters analyzed (parent material, humification, density, moisture content, and conductivity). The ground-based profiles did indicate quite distinct layering within the deposits, but the physical significance of these internal interfaces has yet to be determined. The presence of obstacles (presumed to be boulders or woody remains) was also detected. By providing continuous rather than point data, the profile records provided a very detailed portrayal of the deposit bottom.

3) Q: What are the effects of system frequency?

A: Ground-based data acquired with the 80 MHz antenna yielded the clearest and most detailed results. Attenuation was extremely high for the 400 MHz data, rendering it virtually useless, although some bottom reflections were recieved at depths of up to 2.0 metres. Only minimal differences were observed between the airborne data collected at 80 MHz and 120 MHz.

4) Q: How is the system performance affected by deployment from an airborne platform?

A: In order for sufficient energy to penetrate the air/peat interface, it was necessary to maintain the radar antenna within approximately 2 metres of the deposit surface. Airborne profiles acquired from an altitude of 1.5 metres were much less distnct than ground-based profiles, and were more strongly affected by systematic and random noise. However, the bottom reflections were sufficiently strong to allow depth measurements up to 4.8 metres, the deepest point overflown. Data recorded with the airborne system when the helicopter was set down on the surface

appeared to be comparable with ground-based measurements. Differences were observed in the propagation velocities calculated using airborne data, but were probably due to poor track recovery.

5) Q: What are the effects of deposit types?

A: One fen deposit was included in the study, but no 80 MHz data could be collected for it because the peat was too shallow to be resolved. The 400 MHz profiles were too poor in quality to be analyzed quantitatively. Of the five bog deposits, one (a slope bog) exhibited a significantly higher propagation velocity than the others; it is not known what factors were responsible for this effect. Although the five bogs differed according to their surface morphology, they could not be characterized in terms of any dominant peat parameter. The variation in predicted depth values differed between deposits, but this was likely caused by the effects of bottom roughness on the 'ground truth' measurements, rather than differences in deposit type.

6) Q: What effects are associated with seasonal variations?

A: No significant differences were found between data collected during the summer and fall. Only airborne data was collected during the winter field program and this could not be analyzed quantitatively because of a lack of reliable 'ground truth' measurements. A thin layer of peat (10 to 15 centimetres) was frozen at the time of the winter data collection, but could not be resolved on the profile records. It was hypothesized that a thicker frozen layer should be detectable, and might have a noticable effect on the radar propagation velocity.

Impulse radar techniques can contribute to several levels of peat resource assessment. However, since they do not appear to provide any information on the quality of the peat, they would seem to be most suited for reconnaissance level surveys. Peat volume estimates based on radar profile records were in close agreement with those calculated from manual depth measurements. The use of a single propagation velocity for all deposits is acceptable if relative accuracy only is required; however, it may be necessary to determine the velocity within individual deposits in order to minimize absolute errors. For the five bog deposits analyzed, the composite radar velocity at 80 MHz was 0.036 metres per nanosecond, corresponding to a dielectric constant of 68.8. The attenuation of the radar signal in peat at 80 MHz was estimated as 8.72 decibels per metre from one experiment.

III RECOMMENDATIONS

The utility of impulse radar for measuring peat thickness has been established, and the technique can now be applied as an operational tool. However, there are a number of areas in which further investigation is warranted, in order to extend the range of useful information which can be derived.

Firstly, it would be desirable to test the technique over a greater number of deposits, in order to study more fully the range of radar propagation velocities. This would allow a study of regional differences (where peat has formed under different climatological conditions) and provide a larger data base for statistical comparison of various deposit types (especially deeper fens). It would also serve to define the limitations of the technique, since maximum penetration depths could not be determined for either ground-based or airborne profiling during the present study. Testing of peatlands in permafrost areas would be valuable, since a large proportion of Canada's peat resources lie within these regions.

The major limitation of impulse radar in inventory programs seems to be the fact that it can only measure the quantity of peat present, rather than the quality (degree of humification or botanical constituents) of the material. Although the preliminary analysis was not immediately encouraging, it may yet be possible to relate the layering observed on the profile records to some change in physical or chemical properties. Additional research into this phenomenon could prove to be extremely valuable if it becomes feasible to eliminate or significantly reduce the need for manual sample collection.

The reflection strengths of different bottom materials was not investigated during this study, since the nature of the substratum was not always apparent from the surrounding terrain, and the Hillier sampler could only be pushed easily through the relatively soft peat. It is known, however, that the strength of a return is dependent upon the difference in dielectric properties on either side of an interface and it may be possible to characterize the underlying media by calculating reflection coefficients. This would require some additional processing to eliminate noise and gain effects (as was done for the attenuation experiment) and would require a knowledge of the dielectric constants for typical bottom materials. This type of information would be useful for engineering applications (e.g. road or pipeline construction) as well as for inventory purposes.

Finally, research should be directed towards improving the quality of airborne peat profiling, with the eventual objective of developing a radar system specifically for this application. If the level of information provided by ground-based measurements could be combined with the speed and mobility of a helicopter platform, it seems certain that all levels of peat inventories would benefit substantially. Such research would require an evaluation of the optimal centre frequency, impulse waveform, power requirements, and receiver gain characteristics. Automatic noise removal should also be investigated as well as different

signal enhancement techniques. Hopefully, the operating altitude for airborne profiling can be increased, which would allow data collection over treed deposits. The development of this type of system would contribute not only to peat inventory programs, but also to a wide variety of other geotechnical investigations.

CHAPTER 1

INTRODUCTION

1.1 GENERAL

Once regarded as unusable and an obstacle to development, the peatlands of Canada are now becoming recognized as a major natural resource. Of particular interest is the use of peat as an energy fuel, which has been spurred by the increased cost and diminishing supply of petroleum. According to some estimates Canada has the most extensive peatlands of any nation (Kivinen and Pakarineu, 1980), yet only a small fraction of these reserves has actually been surveyed (Tibbetts, 1980). In order to effectively develop and manage this resource, accurate inventories are required.

The areal extent of peatlands can be measured from aerial photographs and on a regional scale from satellite imagery. However, the area of peatland is often not particularly helpful in estimating the volume of peat present (Pollett, 1978). The depth of a deposit depends upon local climatic and topographic factors, and may vary from a few centimeters up to 25 meters for some sphagnum bogs (Ibid). Traditionally, peat volume estimates within a region are determined by multiplying the peatland area by an average deposit depth, obtained by manual point sampling of depth from a small number of representative deposits. The validity of this technique depends upon the number of the sampled deposits and the sampling intensity within each deposit.

Manual depth measurement is a time-consuming and hence a costly procedure, particularly if peatland areas are extensive. A method of remote depth measurement could greatly reduce the cost of this data collection, or allow more deposits to be sampled. Such a method has been developed for measuring ice thickness, permafrost layers, and rock strata; namely, impulse (or ground penetrating) radar. Accordingly, in response to an unsolicited proposal, Remotec Applications Inc., of St. John's, Newfoundland, was awarded a contract by the Renewable Energy Office of the National Research Council (NRC) to investigate the use of impulse radar techniques for depth profiling of peat deposits. Field data was acquired at a number of deposits in eastern Newfoundland and was subsequently analyzed in both analog and digital formats. This report presents the findings of that study.

The first chapter provides background information on peat and peatlands and a brief description of impulse radar systems and their application. An outline of the project objectives concludes this chapter. Chapter 2 deals with impulse radar techniques in general and specifically with the radar systems employed on this project. This will provide a clearer understanding of the analysis procedures and results. Chapter 3 describes the data collection methodology, including site descriptions, types of measurements, and a summary of the data acquired. The analyses undertaken and the results obtained are discussed in Chapters 4 and 5, respectively. In Chapter 6, the application of the technique into existing or proposed peat inventory programs is evaluated. The final chapter presents conclusions for the study as a whole, and offers recommendations regarding further research.

1.2 PEAT AND PEATLANDS

Peat is partially decomposed plant matter formed in wet areas where atmospheric oxygen is excluded. The accumulation of this organic material is more rapid than the decay, causing a build up of deposits

over a period of time. Peat deposits represent a first stage in the coalification process (Monenco, 1981). Peatlands are recognized land forms which possess a significant organic soil layer formed in a poorly drained site, and are important both from geological and biological points-of-view.

At present, there are no universally accepted classification systems either for peat itself, or for peat deposits. The physical and chemical properties of peat can vary widely within or between deposits. Two common descriptors of peat material are the degree of humification (decomposition) and the type of flora from which the peat is formed. The Von Post Scale of Humification, developed in the 1920's, is a widely used field measurement and has served as the basis for several more recent classification systems (Table 1.1). Although a wide range of flora are associated with peatlands, peats can generally be described as sphagnum, sedge, or woody in origin.

Many local names have been used to describe peat deposits, which has led to some confusion in comparing peatlands from different regions. A recent attempt to standardize peatland nomenclature in Canada has been undertaken by the National Wetlands Working Group in the form of Canadian Wetlands Registry (CWR). Wetlands include peatlands, as well as other areas influenced by excess water (Tarnocai, 1980). The CWR uses a three level classification system, distinguishing class, form, and type (see Appendix A). The two major peatlands classes are bogs and fens; although marshes and swamps may also contain peat, these deposits are not normally suitable for peat extraction. Bogs are generally ombrotrophic (i.e. they receive nutrients from the atmosphere, rather than from surrounding mineral soils) and thus have very low nutrient levels. The dominant bog vegetation species are sphagnum mosses, together with sedges, herbs, and dwarf shrubs; this is reflected in the peat material, which is largely composed of sphagnum remains. Fens are generally minerotrophic and are correspondingly richer in nutrients. They support a greater variety of plant species, and the organic material consists largely of sedge remains, often with sphagnum or woody remains present (Pollett and Wells, 1980).

Von Post Number	Degree of Decomposition	Plant Structure	Mud Present	When Squeezed:		
				Water Released	Amount of peat escaping between fingers	Description of Residue
1	Completely undecomposed	Plant remains easily identifiable	Nil	Clear and Colorless	Nil	Plant remains
2	Almost completely undecomposed	Plant remains easily identifiable	Nil	Clear or Yellowish	Nil	Plant remains
3	Very slightly decomposed	Plant remains identifiable	Little	Muddy brown	Nil	Plant remains
4	Slightly Decomposed	Plant remains have lost some identifiable features	Some	Very muddy, dark	Nil	Plant remains slightly pasty
5	Moderately decomposed	Plant remains quite indistinct, possible to recognize certain features.	Moderate amount	Very muddy	Very small amount of amorphous granular peat	Strongly pasty residue
6	Moderately to Strongly decomposed	Indistinct, see Description of Residue column	Moderate amount	Small amount very muddy	About one third	Strongly pasty, shows plant structure more distinctly than unsqueezed peat
7	Stongly decomposed	Very faintly recognizable plant structure	Large amount	Small amount, if any very dark and almost pasty	About one half	
8	Very strongly decomposed	Very indistinct plant structure	Large amount	A small quantity of pasty water may be released	About two thirds	Residue of roots and fibres that resist decomposition
9	Almost completely decomposed	Almost no recognizable plant structure	Almost entirely muddy		Almost all as a fairly uniform paste	
10	Fully decomposed	No discernable plant structure	Entirely muddy	No free water	All, as a uniform paste	No residue

TABLE 1.1 - VON POST SCALE OF HUMIFICATION

In a natural state, peatlands are an important wildlife habitat and with proper drainage may also support forestry or agricultural activities. Extractive uses of peat can be divided into energy and non-energy uses, each of which require different types of peat material. Moderately to strongly humified peat is more suitable for energy generation; slightly humified peat ("peat moss"), because of its greater porosity and moisture retention capacity, is used for non-energy purposes: as a soil conditioner, filtering medium, or insulation material (Monenco, 1981). Sphagnum peats, most commonly associated with bogs, are generally better for non-energy applications although fuel peat may be extracted once the surface moss has been removed. Fens, which usually contain more strongly humified sedge peat, may also be quarried for fuel peat although they tend to be shallower than bogs.

1.3 IMPULSE RADAR

Impulse radar systems are active sensors that transmit short duration pulses of electromagnetic energy over a relatively wide frequency band, and receive reflected pulses from interfaces where there are marked changes in dielectric properties. Unlike many other remote sensors, they can be used to probe beneath the surface of the terrain, and are thus sometimes referred to as ground penetrating radars. Their ability to penetrate various media has led to the development of several subsurface profiling applications. In operational use since 1970, impulse radar systems have been developed in the HF (3-30 MHz), VHF (30-300 MHz), UHF (300-1000 MHz), S-band (2000-4000 MHz), and X-band (8000-12000 MHz) frequency ranges. Generally speaking, lower frequencies provide better penetration at the expense of coarser resolution.

Originally developed as a shallow subsurface profiler for geophysical applications (Morey, 1974), impulse radars have since been used for profiling glaciers and ice shelves (Watts and Wright, 1981); measuring sea ice and freshwater ice thickness (Campbell and Orange,

1974; Chizhov et al, 1977); iceberg draft measurement (Rossiter and Gustajtis, 1977); mine profiling in coal, salt and dolomite; permafrost studies (Annan and Davis, 1976); mapping buried chemical waste disposal sites (Horton et al, 1981) and the detection of oil layers under ice (Mann, 1979; REMOTEC, 1981). Some preliminary investigations have been carried out in the United States (GSSI) and in the Soviet Union (Bogorodskii and Trepov, 1979) for measuring peat depth with impulse radar.

Impulse radars systems do not measure depth directly, but rather record the returned signal strength as a function of time. In order to translate the time delay between transmission and reflection into units of distance, it is necessary to know the speed of the wave through the medium. This may be calculated if the dielectric constant of the material is known or can be determined. The dielectric properties of earth materials are strongly influenced by their composition and moisture content and variations in these factors must be taken into consideration when analyzing impulse radar data.

1.4 SCOPE AND OBJECTIVES

The overall purpose of the study was to assess the use of impulse radar techniques for depth profiling of peat deposits. If successful, these techniques could be applied to peat inventory programs to obtain faster and/or more accurate estimates of peat volume at a lower cost than manual measurements. Tests were carried out at a number of peat deposits on the island of Newfoundland; "because of their accessibility and heterogeneity, the peatlands of Newfoundland may be used to provide insight and appreciation of those peatlands across Canada which cannot easily be visited" (Pollett and Wells, 1980). It was felt, therefore, that results obtained from these sites could be replicated elsewhere.

Specific objectives were identified in order to make a complete assessment of the technique. These objectives can be stated as a series of questions, namely:

- does the technique provide consistent and reliable measurements of peat thickness?
- can the technique provide any additional information on the peat composition or the deposit structure?
- what are the effects of system frequency?
- how is the system performance affected by deployment from an airborne, rather than ground-based, platform?
- what are the effects of deposit types?
- what effects are associated with seasonal variations?

Information derived from the analysis of the radar data was used to determine the dielectric properties of the peat material and characterize the sensor/target interactions. Based on these findings, and the experience gained in field data collection, the operational potential of impulse radar systems for inventorying peat resources was evaluated.

CHAPTER 2

IMPULSE RADAR TECHNIQUES

2.1 THEORETICAL CONSIDERATIONS

Impulse radar systems transmit short duration pulses which cover a relatively wide frequency band. Each pulse may be thought of as a single cycle of a wave made up of a series of component frequencies. Shorter pulse lengths and smaller side lobes require higher frequency components. The frequency characteristics of the transmitted pulse (centre frequency and bandwidth) are largely determined by the antenna characteristics. In some newer systems (mostly under development), the sequence of pulses is formed by mixing waveforms at a fundamental frequency and its harmonics. This allows better control on the shape and duration of each pulse.

A reflecting surface, such as the interface between two media, can be detected if sufficient energy is reflected back to the receiving antenna. The strength of the reflection is dependent upon the difference in permittivity between the two media. The absolute permittivity (ϵ) of a material is a complex term, composed of two components:

$$\epsilon = \epsilon' + \epsilon'' \qquad (2.1)$$

where ϵ' = the real component
and ϵ'' = the imaginary component

The real component determines the velocity of the electromagnetic energy, while the imaginary component determines the attenuation. Both components

are frequency dependent, although this dependence is much more significant for the imaginary (loss) portion. In geophysical materials (Morey, 1974) and in sea ice (Rossiter, 1979) the signal attenuation increases sharply with increasing centre frequency. The attenuation (normally expressed in decibels/metre) determines the depth to which the energy can penetrate.

A more commonly used term is the dielectric constant or relative permittivity which is defined as the ratio of the absolute permittivity of a medium to the absolute permittivity of free space (ϵ_0 which is equal to 8.8542×10^{-12} coulomb^2/newton metre^2). There is no signal attenuation in free space and the imaginary component is ignored. This term (which is also known as the bulk dielectric) can be used to determine the velocity (V) of the radar impulse in a medium:

$$V = c / \sqrt{\epsilon_r} \qquad (2.2)$$

where c = speed of light in a vacuum
and ϵ_r = dielectric constant of the medium

Thus, as the dielectric constant increases, the velocity of propogation is reduced. Once the speed of the radar wave is known, the travel time between transmission and reception can be converted into units of distance.

2.2 MONOSTATIC/BISTATIC OPERATION

An impulse radar system consists of: one or two antenna(e); a control unit; a magnetic tape recorder; a grey scale plotter (which may or may not be connected to the system during data collection); and an external power supply (Figure 2.1). In bistatic operation two antennae are employed: one as a transmitter, the other as a receiver. In monostatic operation a single antenna is used as a transceiver.

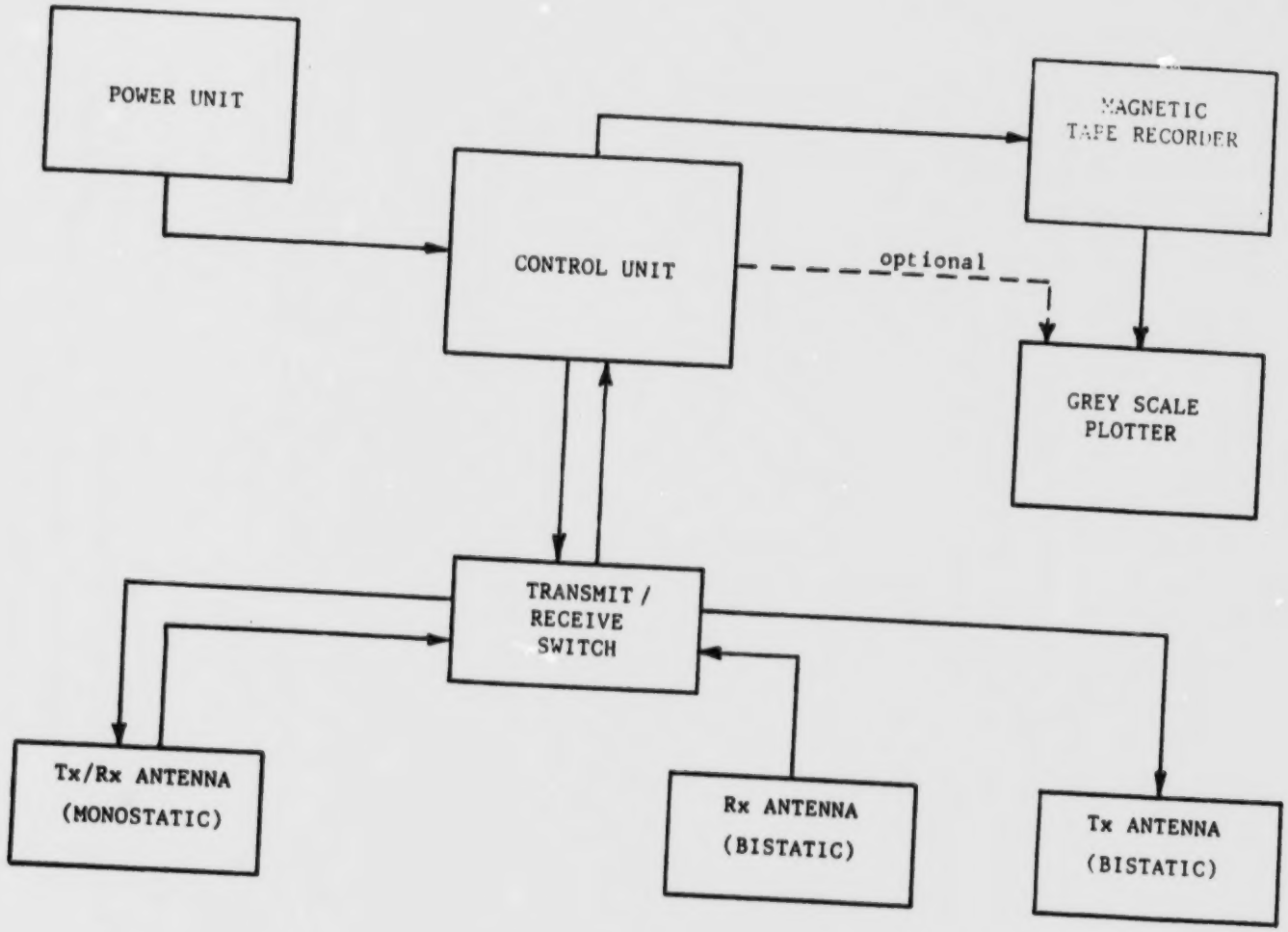


FIGURE 2.1 - BLOCK DIAGRAM SHOWING COMPONENTS OF AN IMPULSE RADAR SYSTEM.

During monostatic operation, a clipped version of the transmitted pulse is detected immediately by the receiver through the transmit/receive switch. The next pulse received is a reflection from the antenna/medium interface, although this may not be large in amplitude. Even if the antenna is coupled directly to the medium, the difference in dielectric properties between the antenna and the medium causes some of the transmitted energy to be reflected. As the pulse passes through the medium, it experiences attenuation and minor partial reflections. A stronger reflection normally marks the interface between different media, depending upon the difference in dielectric properties and the nature of the transition. The reflected pulse then propagates back to the surface, undergoing the same attenuation and partial reflections as before. The transmitted pulse continues to pass through underlying media and, if there is sufficient energy, additional interfaces may be detected.

While the general principles remain the same, there are a few significant differences between monostatic and bistatic operation. In bistatic operation, the first pulse to reach the receiving antenna is a direct wave which propagates through the air from the transmitting antenna (airwave). This is normally followed by a groundwave passing between the antennae just below the surface of the medium. The radar wave reflected by the interface undergoes the same attenuation and reflection as in the monostatic case; however, the total path length of the reflected wave (from the transmitter to the reflector to the receiver) will be greater. The increase in distance travelled by the pulse (in comparison to monostatic operation) will depend on the distance between the antennae and the depth of the reflector.

The increase in path length associated with bistatic operation can be used to obtain a field measurement of the dielectric constant (and hence the propogation velocity) using a technique known as Wide Angle Reflection and Refraction (WARR), described by Annan and Davis (1976). Figure 2.2 illustrates the procedure; the two antennae are first set up side by side on a level area above the reflecting interface. They are

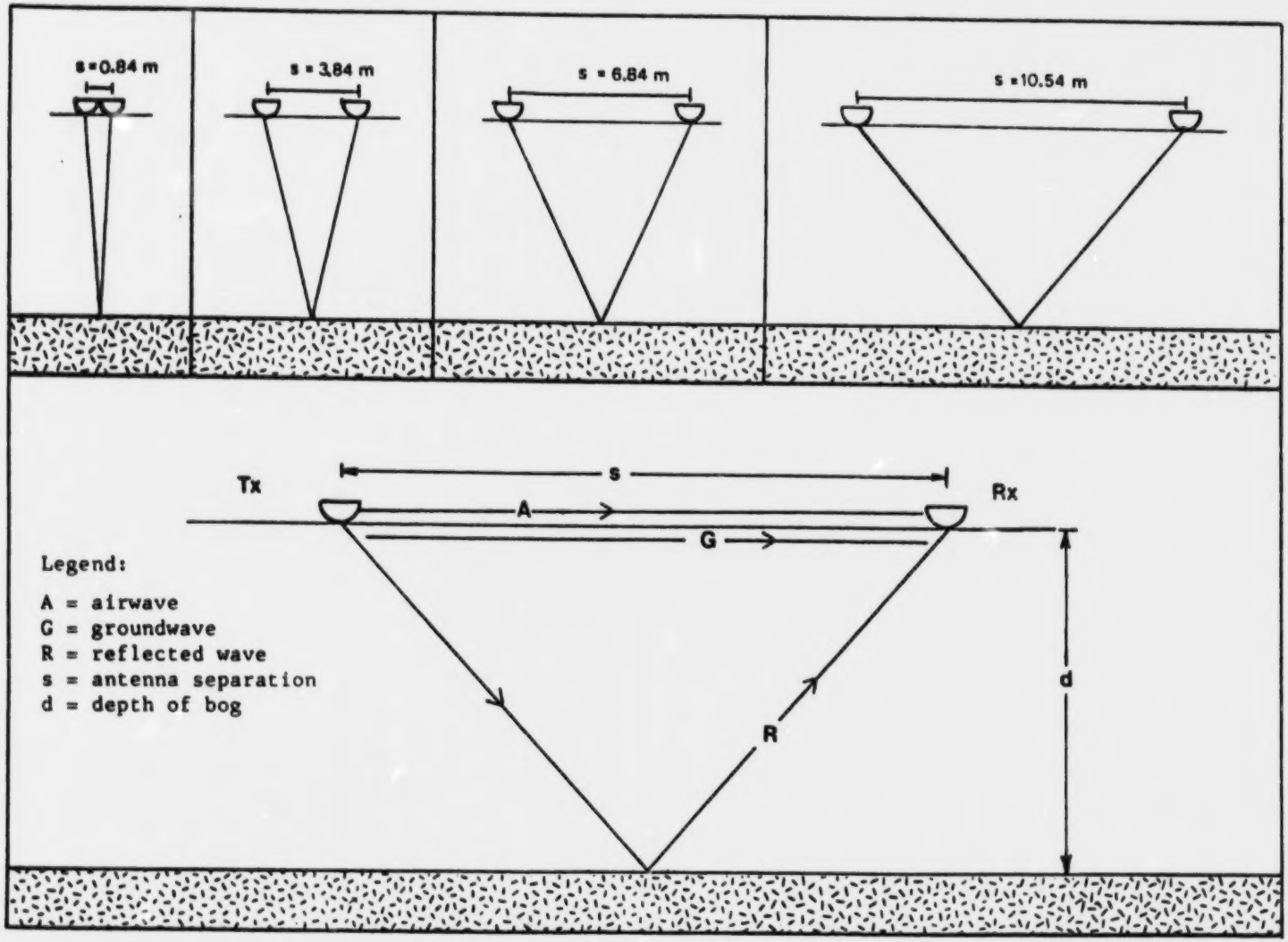


FIGURE 2.2 - WIDE ANGLE REFLECTION AND REFRACTION MEASUREMENTS
(Incremental Antenna Separation)

then moved away from each other (either at a constant rate or in a series of incremental steps) while recording the radar signal. The arrival times for the airwave (t_A), ground wave (t_G), and reflected wave (t_R) are given by:

$$t_A = s / V_A \tag{2.3}$$

$$t_G = s / V_G \tag{2.4}$$

$$t_R = \sqrt{s^2 + 4d^2} / V_G \tag{2.5}$$

where s = antennae separation distance
V_A = propagation velocity in air
V_G = propagation velocity in medium
and d = depth to interface

In cases where the ground wave can be detected, the value of V_G can be easily calculated, since both s and t_G are known. The dielectric constant can then be determined by:

$$\epsilon_r = c^2/V_G^2 \tag{2.6}$$

However, if the ground wave does not appear on the record (i.e. the signal strength is below the detection threshold of the receiver), the reflected wave may be used instead. Equation 2.5 may be rewritten as:

$$s^2 = (V_G)^2 (t_R)^2 - 4d^2 \tag{2.7}$$

By plotting the square of the antennae separation distances as a function of the square of the observed reflected wave arrival times, the resulting linear fit will have a slope of V_G^2 and an intercept of $-4d^2$. This technique is useful where the depth to the reflecting interface is unknown and cannot be easily measured. The derived value of V_G can again be used to calculate the dielectric constant using Equation 2.6.

2.3 SYSTEM DESCRIPTIONS

Two impulse radar systems were employed in this project: a GSSI Subsurface Interface Radar System 7 was used for all of the ground-based measurements, while a C-CORE Model 100 Airborne Impulse Radar was used for most of the airborne profiling. The C-CORE system was redesigned from the GSSI radar specifically for airborne measurement of sea ice thickness. The manufacturer's specifications for these systems are included as Appendix "B".

The GSSI system was supplied with 80 MHz and 400 MHz antennae. Both monostatic and bistatic operation were possible with the 80 MHz antennae, while the 400 MHz antennae had to be used in a bistatic mode. The antennae contain resistively loaded dipole elements that radiate and receive the radar impulses, together with transmitting and receiving electronics. The receiving electronics include sampling equipment used to shift the UHF signal into the audio frequency range (0-20 KHz) so that it can be recorded on analog magnetic tape. The control unit, in addition to regulating the transmitter and receiver functions of the antenna(e), is also used to control the scan rate, window length, time varying gain, and filtering and the recorder, plotter, and CRT display. Modifications were made to the GSSI control unit by C-CORE to provide adjustable time ranges and improved timing control for tape recording and to improve the total system performance.

The C-CORE airborne system is equipped with a single (monostatic) 120 MHz antenna, which can be mounted beneath a Bell 206 helicopter by means of a frame attached to the helicopter's cargo hook. This antenna is shielded to minimize reflection and 'ringing' from the helicopter and has a built-in radar altimeter. Output from the altimeter can be recorded on tape to allow the removal of any altitude variations in the data. The pulse repetition frequency (and hence the scan rate) has been increased to allow profiling at higher speeds. The C-CORE control unit offers two selectable window lengths and a choice between four

selectable window offsets or automatic signal positioning controlled by the radar altimeter. Unlike the GSSI unit, the gain controls are calibrated, and are in discrete steps rather than being continuously variable.

CHAPTER 3

DATA COLLECTION

3.1 SITE DESCRIPTIONS

Impulse radar measurements were made at six peat deposits on the island of Newfoundland (Figure 3.1). The sites were selected on the basis of accessibility, deposit type, and depth. In most cases, unofficial names were used to describe the deposits (based on location and class) since local names were either non-existent or unknown.

The Fort Motel Bog is situated just east of the Trans-Canada Highway (TCH), approximately 10 kilometres southwest of St.John's. This bog is at the headwater of the Waterford River and has been used for previous demonstration projects by the Canadian Forestry Service. Large areas of the bog had been ditched several years previously, which prevented ground based profiling over much of the deposit. However, it was planned to use the ditches for the insertion of metal reflectors, until a more suitable site was found. Because of its proximity to St. John's, this deposit was convenient for the initial testing of equipment and procedures.

The Witless Bay Bog and Witless Bay Fen are part of a large bog/fen complex located near the western end of the Witless Bay Line (Route 13), near the TCH. The former is a slope bog of moderate depth while the latter is a patterned fen with a relatively shallow peat layer. Numerous rock outcroppings are evident throughout this area, suggesting that both deposits are underlain by bedrock.

No.	Name (unofficial)	U.T.M. Zone	Alpha Let.	100,000 m^2	Easting	Northing
1	Fort Motel Bog	22	T	CH	6030	6270
2	Witless Bay Fen	22	T	CH	4710	4460
3	Witless Bay Bog	22	T	CH	4690	4450
4	Whitbourne Bog	22	T	CH	1560	5740
5	High Point Bog	21	U	XE	1550	3350
6	Jonathan's Pond Bog	21	U	XE	8380	4620

FIGURE 3.1 - LOCATION OF TEST SITES

The Whitbourne Bog is a raised bog adjoining the south side of the TCH, approximately 7 kilometres east of Route 80. This was the largest and deepest deposit studied on the Avalon peninsula, and was therefore the most extensively sampled.

The High Point Bog is situated near Bishop's Falls, 3.5 kilometres north of the junction of the TCH and Route 42. At the time of the field programs, a section of this deposit was being harvested as part of a fuel peat demonstration program. The surface layer of moss had been removed and ditches had been excavated to the bottom of the peat. One of these ditches was used for an attenuation experiment, which involved the insertion of metal reflectors at known depths. WARR measurements were also carried out in this area and on the unditched portion of the bog (which retained its natural cover) together with depth profiling.

The Jonathan's Pond Bog is located 25 kilometres north of Gander on Route 330, 14 kilometres north of Jonathan's Pond. It is a large raised bog, with a surface area of about 1 square kilometre. This was the deepest deposit studied during the program, and was selected to test the maximum depth detectable by the radar system.

3.2 FIELD PROGRAMS

Data were acquired during three field programs, in summer (July-August), fall (October-November), and winter (March). Both ground-based and airborne data were collected in the first two programs, while the final program consisted solely of airborne measurements. The three field programs allowed seasonal variations to be observed and permitted modifications in the data collection after preliminary analysis of the preceding data set.

Prior to the start of the first field program, candidate

deposits close to St. John's were visited with Mr. Doyle Wells of the Newfoundland Forest Research Centre (NFRC). Mr. Wells also provided information on other deposits in central Newfoundland which could be used for the study. A preliminary list of test sites was then drawn up, and aerial photographs and maps of these areas were acquired. A tow sled for transporting the radar antenna over the terrain was constructed, while surveying and sampling equipment was obtained.

The first program served to demonstrate the feasibility of the technique, at least from a ground-based platform. Four deposits were studied using the GSSI radar with both the 80 MHz and 400 MHz antennae; one other deposit was studied using the 400 MHz antennae only. The results were encouraging, especially with the 80 MHz antennae, as clear bottom reflections could be seen on the profiles. The attenuation experiment was carried out at the High Point Bog, but was not immediately successful. During the first airborne experiments, the four deposits on the Avalon Peninsula were overflown using the 120 MHz radar. However, the initial altitudes selected were apparently too high, and the results were disappointing.

During the second field program, all deposits profiled in the first field program were retested and, in most cases, additional parallel lines were profiled to allow the calculation of peat volumes. Further WARR measurements were made and an experiment was carried out to test the effect of raising the antenna above the bog surface. The attenuation experiment was repeated with greater success. The Jonathan's Pond Bog in central Newfoundland was also profiled for the first time; the maximum depth of this deposit was slightly in excess of 7.5 metres, which was the greatest depth that could be measured manually with the available equipment. Also during this program, intensive sample collection was carried out on the Whitbourne Bog. A second airborne experiment was undertaken in mid-October; the results were ambiguous, suggesting that some bottom reflections were received, but were rather indistinct. In November, additional airborne tests using two frequencies and two

separate control units were carried out over the Whitbourne Bog. These tests involved the 120 MHz antenna and C-CORE control unit, as well as the 80 MHz antenna and the GSSI control unit previously used for ground-based depth profiling. All four antenna/control unit combinations were tested. The results were much better than those previously obtained, particularly after filtering the data.

Winter data collection using the C-CORE airborne system with the 120 MHz antenna was undertaken early in March. Ground-based measurements had also been planned but had to be cancelled, first because of severe weather conditions and later because the GSSI system was unavailable. Tests were confined to the Whitbourne Bog only, as road access to the other candidate sites was blocked by snow. Snow cover over the bog varied from 40 to 60 centimetres in depth, while a frozen peat layer of 10 to 15 centimeters was measured. Two of the lines profiled earlier were reflown; radar measurements were also taken while flying over an open pond in the centre of the deposit and while the helicopter rose vertically above points of known depth. There appeared to be a small improvement in the returned signal in comparison with the previous airborne tests.

3.3 GROUND-BASED MEASUREMENTS

The ground-based component of the field programs consisted primarily of WARR measurements and bottom profiling with the GSSI impulse radar, together with manual depth sounding and peat sample collection. Transect lines were laid out at each site, with sample points marked by stakes at 25 or 50 metre intervals. In order to transport the radar antennae across the surface of the deposits, a wooden sled was constructed which was towed behind an ARGO all terrain vehicle (ATV). The control unit, tape recorder, cable reel, and a McCullough 1500 watt generator were carried in the rear of the ATV (Figure 3.2).

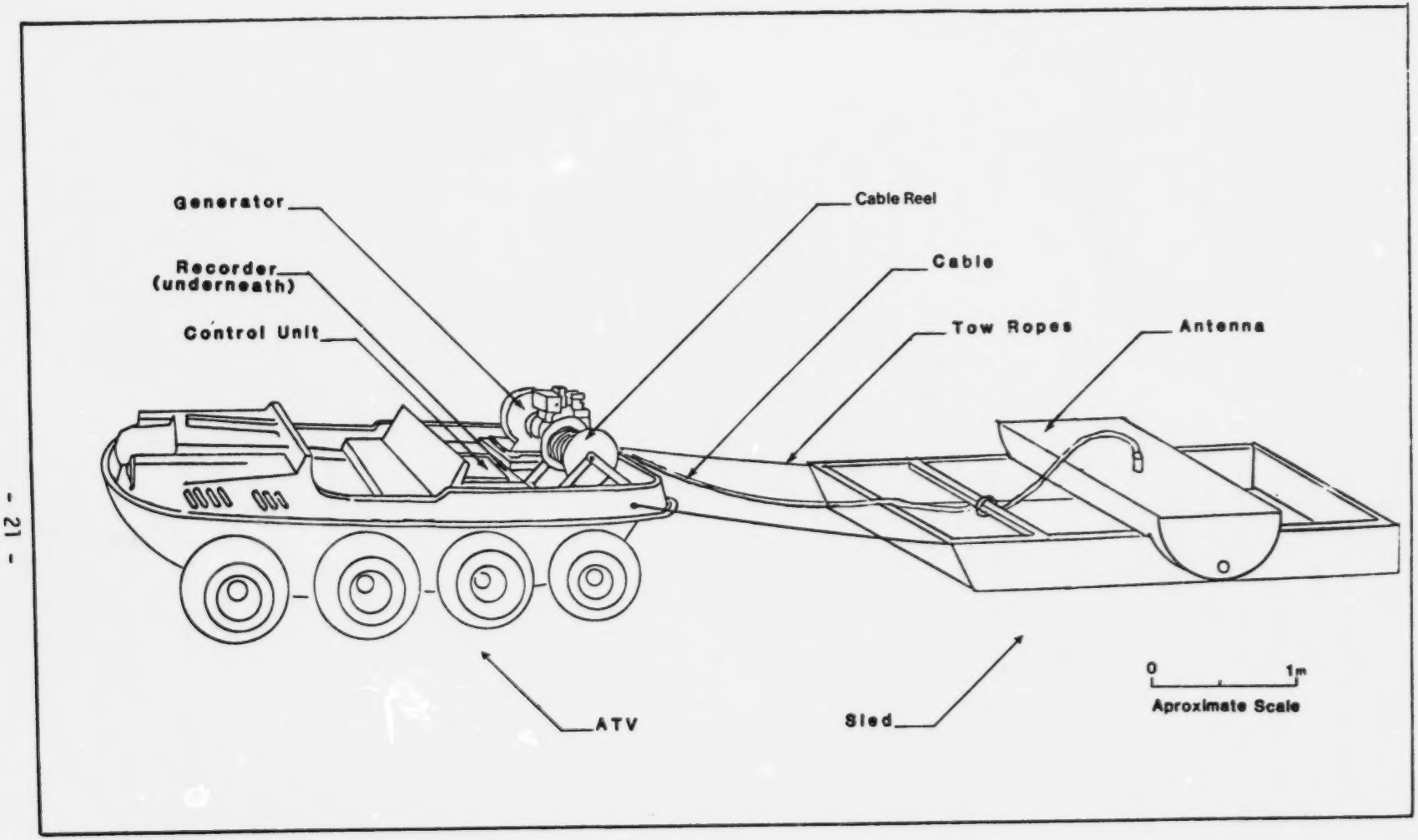


Figure 3.2 - EQUIPMENT CONFIGURATION FOR GROUND BASED PROFILING (80 MHz Antenna)

The procedure for WARR measurements was the same for the 80 MHz and 400 MHz antennae. The two antennae (transmitter and receiver) were set up side by side at a marked location, usually at one of the sample points. A recording was made, and the antennae were separated in increments away from the centre point. Recordings were made at each interval, up to a maximum of 10 metres separation. Incremental steps were used rather than continuous separation, since the gain settings had to be adjusted as the distance between the antennae was increased. A typical set of WARR measurements required approximately 20 minutes to complete.

Profiling with the 80 MHz system was carried out with a single antenna, while the 400 MHz profiling utilized two antennae at a fixed separation of 1 metre. This separation distance was found by experiment to minimize the systematic noise in the radar signal. For both frequencies, the antenna(e) were placed in the sled, which was towed about 5 metres behind the ATV. With the radar system continuously recording, the ATV was driven along each transect line; an event marker was used to indicate the location of each sample point (stake) on the record. The speed of the ATV was governed by the nature of the terrain, but was kept relatively constant between each pair of stakes, averaging approximately 1.8 metres per second (6.5 km/h). Under normal conditions, one person was able to drive the ATV and operate the radar and recording system; however, where the terrain was particularly rough, a separate driver and operator were required.

The attenuation experiment, conducted at the High Point Bog, involved the insertion of metallic reflectors into the peat at known depths. This was possible because of the recent ditching which had been done at this site. The ditches ranged from 1.5 to 1.7 metres in depth, and were approximately 0.75 metres in width. Although the surface peat was relatively dry, the underlying layers still retained much of their moisture content. Metal pipes, 1 metre long and 2.5 centimetres in diameter, were pushed horizontally into the side of the ditch at five metre intervals with a vertical offset of 25 to 50 centimetres. During

the first attempt at this experiment, a single pipe was inserted at each location; during the subsequent attempt, four pipes were inserted side by side at each point. The 80 MHz antenna, operating in a monostatic mode, was pulled along the surface near the edge of the ditch while recordings were made. The antenna had to be moved manually during the first attempt, which meant that it was set back from edge of the ditch, whereas on the second attempt the antenna was pulled behind the ATV, and the edge of the antenna passed immediately over the ditch edge. This was apparently responsible for the success of the second experiment.

The peat depth was measured manually at each sample point using a Hillier sampler, which was also used to collect peat samples from selected points. The Hillier sampler consists of a T-shaped handle, a number of 1 metre extension rods, and a cylindrical coring unit with a small auger at the bottom. With the extension rods available, depths of up to 7.5 metres could be measured. In general, the sampler could be pushed into the peat without much difficulty; however, the process was rather time-consuming, particularly for deeper deposits, since the extension rods had to be attached one at a time as the sampler was inserted and withdrawn. In some deposits, hard layers of woody peat were encountered, and in at least one instance such a layer was mistaken as the deposit bottom until subsequently rechecked. Withdrawal of the sampler was also difficult in a number of cases, requiring two and sometimes three people. This problem was alleviated somewhat by replacing the coring unit with a conical spear point when peat samples were not required. The depths obtained manually represented measurements from single points, whereas each bottom reflection received by the impulse radar was actually a composite return integrated over a "footprint" area. Therefore, after analyzing the radar measurements some additional field work was carried out to determine the variability of manual depth measurements within a one square metre area at different thicknesses of peat. Although no attempt was made to calculate the actual size of the radar footprint, it was felt that this would provide an appreciation of the differences which might normally be expected between single point measurments and "averaged" depth values.

The collection of peat samples for laboratory analysis served different purposes during the first and second field programs. Prior to the start of the first program, it was not known to what extent the radar propagation velocity would vary from one deposit to another. In the event that large differences were apparent, it was hoped that each site could be characterized according to one or more parameters. Therefore, a few core samples were taken at various depths from each deposit studied. After the analysis results of these samples had been examined, however, it became clear that all of the deposits were basically heterogeneous in terms of peat characteristics, while the differences in the average propagation velocities appeared to be slight. During the second field program, attention was focused instead on the layering phenomenon, in the hope that this might be correlated with physical changes in the peat. Samples were collected from the entire peat column at 5 metre intervals along a portion of one of the transect lines on the Whitbourne Bog, where the layering was most evident. In both field programs, the same sample collection procedures were followed: a field assessment was made of the degree of decomposition (using the Von Post scale), notable features and characteristics were recorded, and the samples were then stored in plastic bags and labelled. The laboratory analyses, described in section 4.6, were carried out at the NFRC soils lab.

3.4 AIRBORNE MEASUREMENTS

The airborne measurements consisted of profiling along the previously established transect lines, together with point sounding with the helicopter touching down on the surface. These measurements were normally carried out using the C-CORE (120 MHz) airborne radar system; however, one series of tests was carried out with the GSSI control unit and 80 MHz antenna for purposes of comparison. In the latter instance, the mounting frame supplied with the C-CORE system could not be used, and the antenna was suspended in a cargo net approximately 2 metres below the helicopter. Both systems utilized the helicopter's onboard power supply

(28 volts DC). The control unit and tape recorder were set up in the rear passenger area of the helicopter, where they could be operated by a single individual. An observer sat in the front passenger seat to trigger the event marker as each sample point (stake) was overflown.

When used for airborne measurement of ice thickness, the impulse radar is normally operated at an altitude of 30 metres. Therefore, the initial tests over peat deposits were flown at 15 and 25 metre altitudes. These proved to be excessively high as only surface returns were received. After subsequent testing, an altitude of approximately 1.5 metres was found to be usable. Since none of the deposits were tree-covered, this altitude did not present any difficulty for the helicopter. Profile lines were flown at speeds between 10 and 20 kilometres per hour, with the speed held constant along each line. Because the view of the front observer was somewhat blocked, some difficulty was experienced in coinciding the event marker with the exact position of the sample points.

Point depth sounding was undertaken with the helicopter as close as possible to the sample point stakes, usually within 2 or 3 metres. On a few occasions, the recorder was left on as the helicopter rose vertically above the points.

3.5 DATA SUMMARY

The impulse radar data collected from each of the six deposits is summarized in Table 3.1. The number of profiles given in the table includes repetitive coverage of the same transect lines during the three field programs.

Deposit Name	Ground-Based Measurements				Airborne Measurements	
	80 MHz Profiles	400 MHz Profiles	80 MHz WARR	400 MHz WARR	120 MHz Profiles	80 MHz Profiles
Fort Motel Bog	5	1	2	—	6	—
Witless Bay Fen	—	2	—	—	4	—
Witless Bay Bog	5	5	1	1	4	—
Whitbourne Bog	10	2	3	—	17	7
High Point Bog	10	2	3	—	—	—
Jonathan's Pond Bog	3	—	—	—	—	—

TABLE 3.1 - SUMMARY OF FIELD DATA

No 80 MHz data was acquired for the Witless Bay Fen because the shallow depth of the peat was less than the minimum depth resolvable at that frequency. The step-like nature of this deposit and the numerous rock outcrops also made WARR measurements unfeasible, and limited the number of profile lines.

It became apparent after the first field program that the penetration capability of the 400 MHz system was quite limited. Therefore, very little 400 MHz data was collected after this time, except on the Witless Bay Bog which was comparatively shallow.

Airborne data collection was restricted to deposits on the Avalon Peninsula, in order to minimize the cost of helicopter travel time. The use of the 80 MHz antenna in an airborne mode was limited to the Whitbourne Bog only, since the method of suspending the antenna below the helicopter was not suitable for transport over long distances.

CHAPTER 4

DATA ANALYSIS

4.1 DATA PREPARATION

Data collected in the field was recorded on 1/4 - inch analog magnetic tape. In order to obtain a hard copy of this data, the tapes were played back through a Honeywell Visicorder. This device is a grey scale plotter which prints onto light-sensitive 'dry silver' paper. Each radar scan (actually an audio frequency replica of the received radar signal) was plotted as an intensity modulated line across the width of the paper, with positive peaks appearing white and negative peaks appearing black (Figure 4.1). Reflectors within the peat (including the deposit bottom interface) appeared as a series of alternating black and white bands, because of the shape of the impulse waveform.

As each chart was produced, it was annotated as to the location, date of acquisition, and given a profile line or WARR measurement number. The location of the 'ground truth' sample points, indicated on the record by the event marker, was also annotated after reference to the field notes.

The preliminary analysis of the data consisted of identifying the various signals present on the record: transmit pulse, surface reflection, systematic noise, reflectors within the peat (such as stumps or boulders) and bottom reflections. In some cases, strong signals and/or systematic noise tended to override weaker reflections; for example, the large peaks from the transmit pulse usually obscured the surface reflection. The internal reflectors and bottom reflections were, for the most part, readily identifiable on the profile records, since they varied

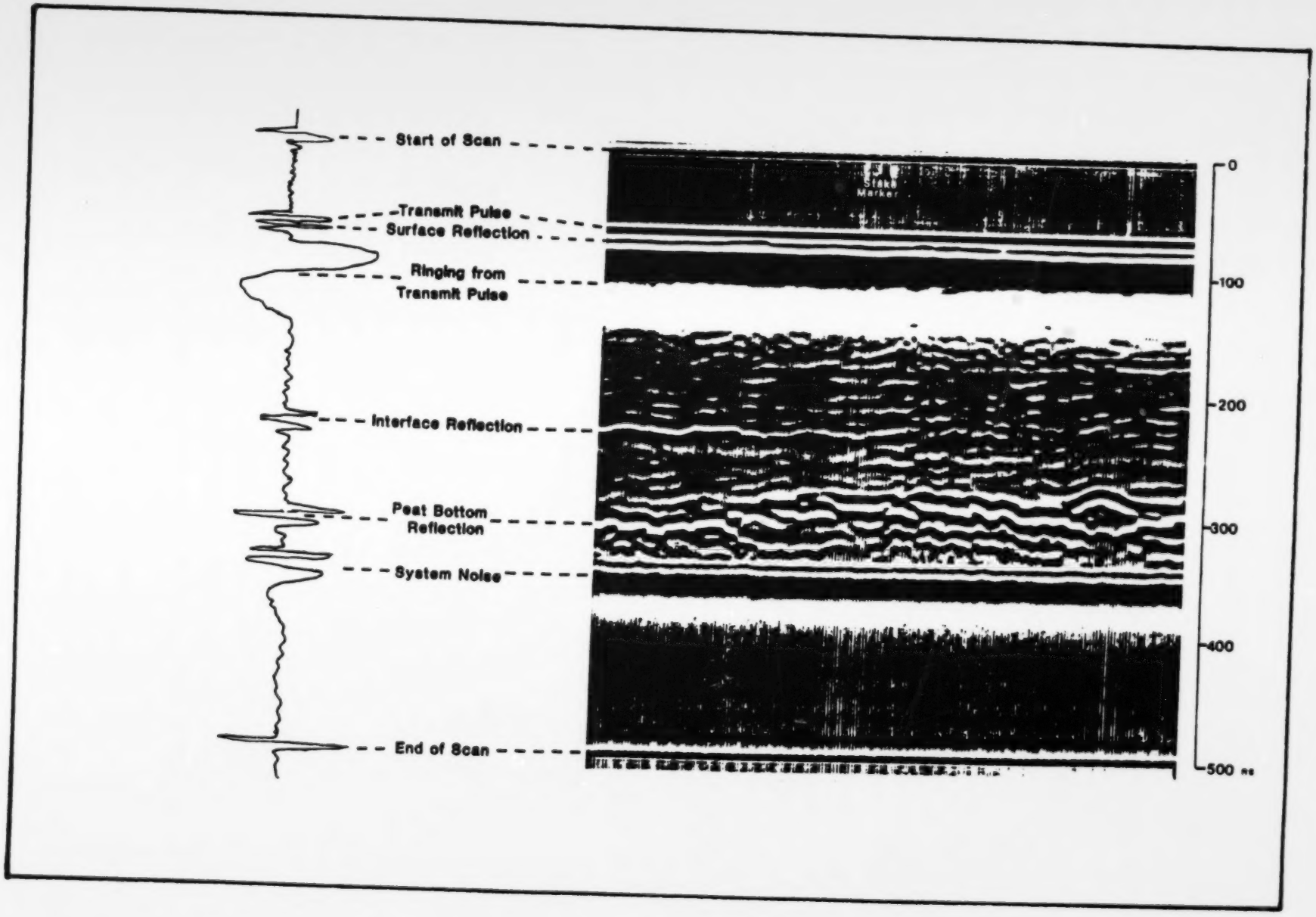


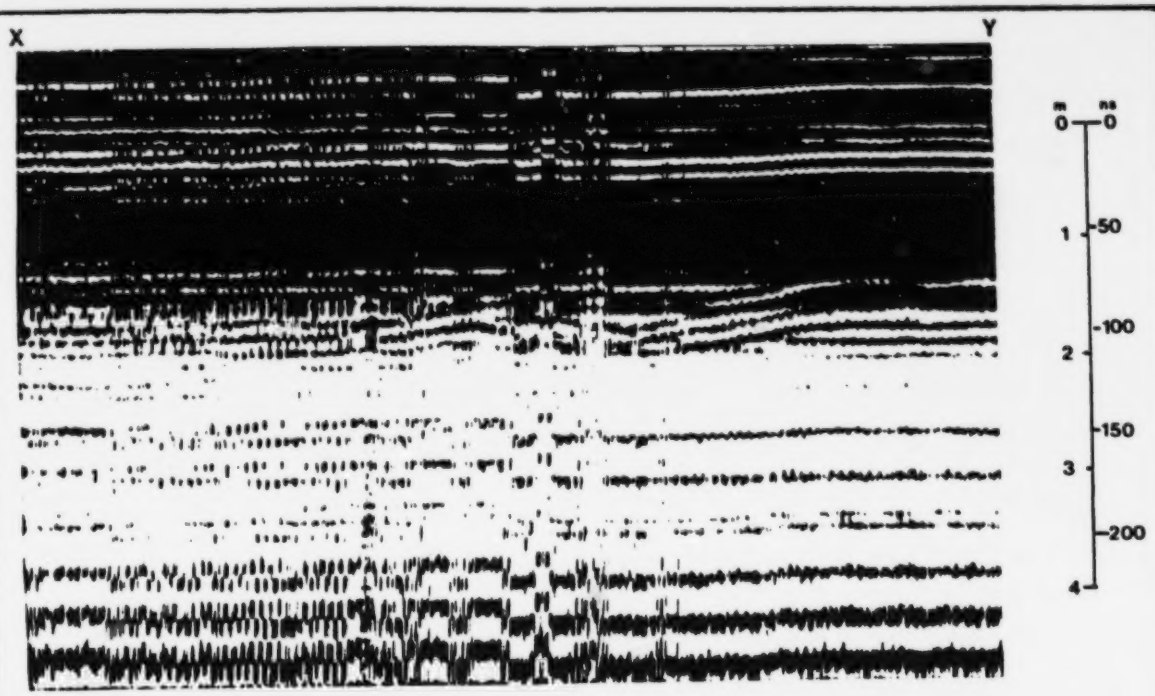
FIGURE 4.1 - INTERPRETATION OF INTENSITY MODULATED PLOT

with time as the antenna was moved across the surface. However, during the WARR measurements, the antennae were stationary while recording at each increment, and the signals were more difficult to separate. For this reason, the WARR recordings were played back through an oscilloscope, which provided an amplitude modulated display of the radar scans. Polaroid photographs were taken of the oscilloscope screen and were used together with the chart recordings to interpret the WARR results.

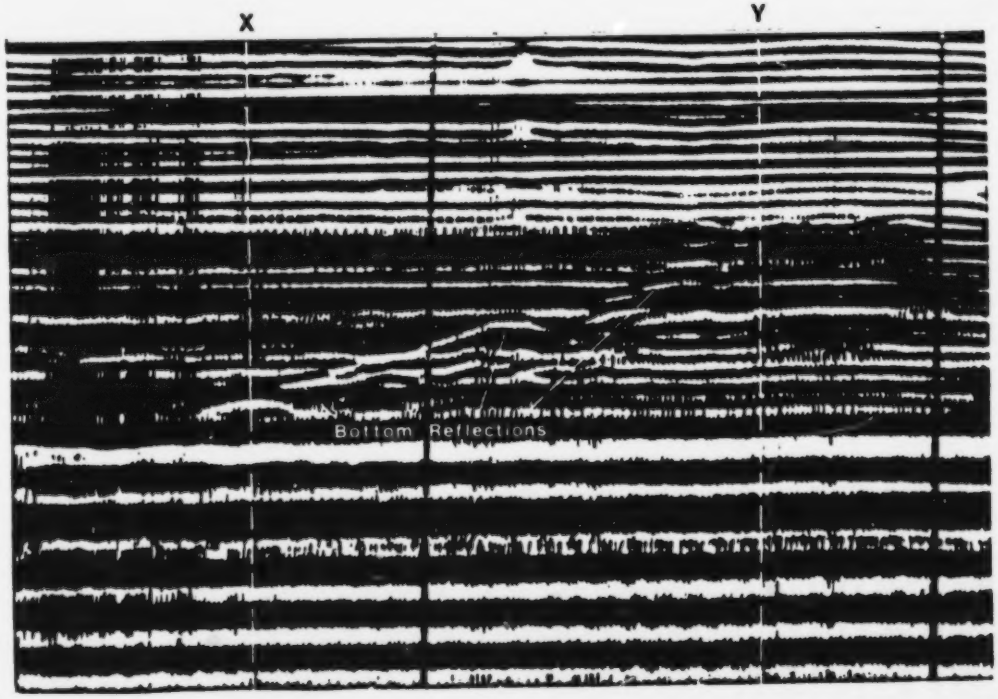
Some of the initial chart recordings from the airborne profiles were of poor quality, making the delineation of the bottom reflections difficult. Wide light and dark bands were present, caused by very low frequency background noise and DC offsets, probably originating from the amplifiers in the control unit due to the high gain settings used. The data tapes were replayed through the Visicorder using a high pass filter to eliminate these components; this greatly enhanced the visual quality of the records (Figure 4.2) and made discrimination of the various signals possible.

4.2 WARR ANALYSIS

The first step in the analysis of the WARR data was the identification of the signals on the chart records (Figure 4.3) and oscilloscope photographs. Although the airwave and the reflected wave (from the deposit bottom) were visible in each case, no groundwaves could be detected. Once identified, the time delay between the signals was measured and recorded; the time scale was calculated by measuring the length of the scan on the record (or photograph) and dividing this into the length of the time window set during the data collection. Since the transmit pulse was not indicated on the record (this is only received during monostatic operation), all of the time measurements were initially referenced to the start of scan. The airwave arrival times were then plotted against the measured antennae seperation distances, and the y - intercept of this line was used to determine the time of the transmit



A. Airborne profile before filtering.



B. Airborne profile after filtering to remove DC and low frequency signals.

Note that the bottom echo is more clearly visible.

FIGURE 4.2 - AIRBORNE DATA FILTERING

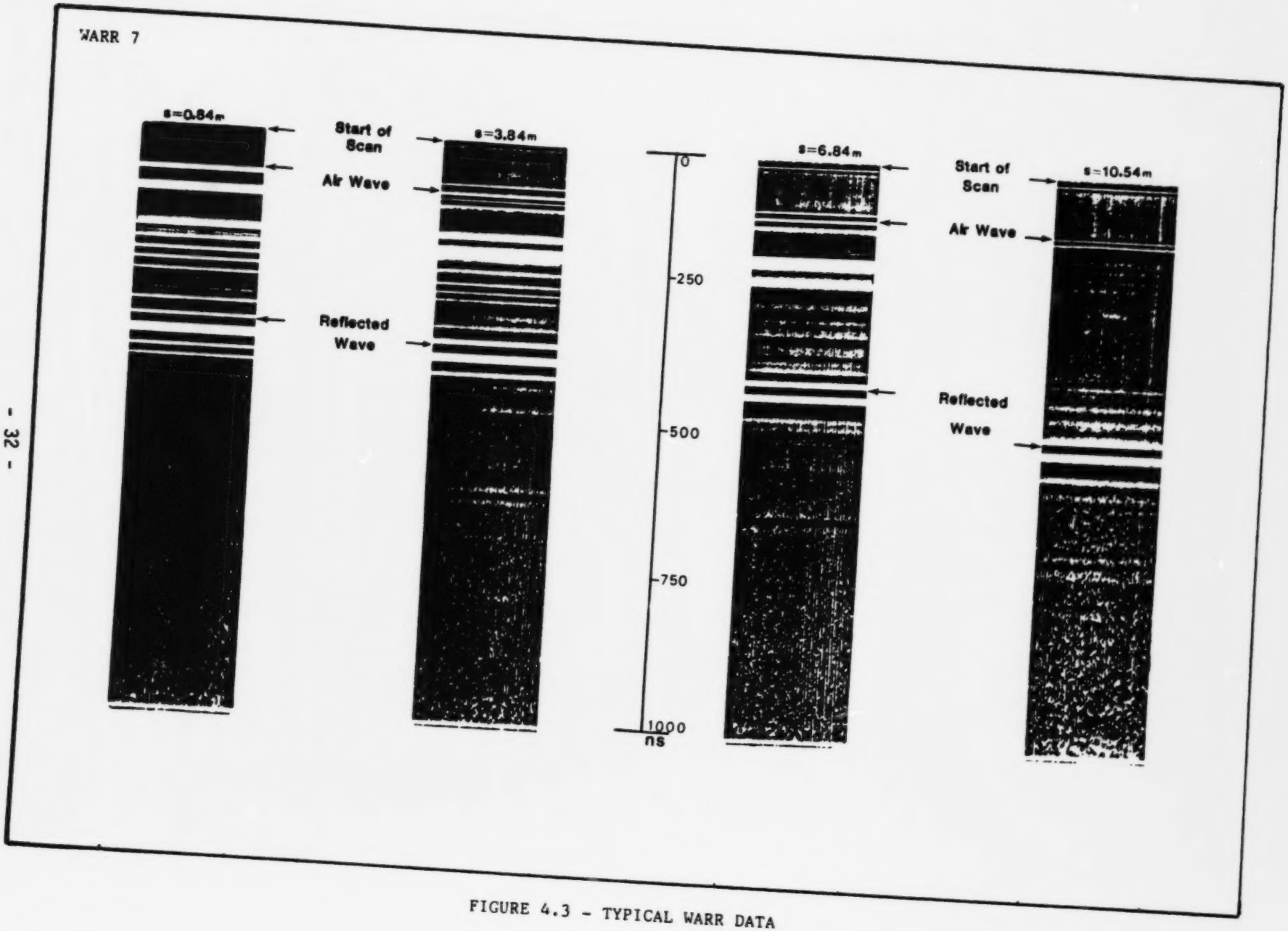


FIGURE 4.3 - TYPICAL WARR DATA

pulse (t_o) with respect to the start of scan (Figure 4.4). The time delay measurements were adjusted accordingly by subtracting t_0 from each value.

Ideally, the velocity of the radar wave in peat would be determined by dividing the groundwave arrival time into the antennae separation distance. However, since the groundwaves could not be detected, a more indirect approach was followed, using the reflected wave arrival times. As described in Chapter 2, a plot of t_R^2 versus s^2 should yield a straight line with slope V_G and an intercept of $-4d^2$ (where t_R = reflected wave arrival time; s = antennae separation distance; V_G = velocity of propagation in peat; and d = depth of the reflecting interface). Such plots were drawn for each of the WARR measurements, and a linear least squares regression was fitted to the points to derive the equations of these lines (Figure 4.5). The propagation velocities obtained with this method were used to calculate the dielectric constant at each site, using Equation 2.6.

The results of this analysis showed a wider range of values than had been expected. Furthermore, the depth measurements calculated from the y - intercepts were not consistent with those measured manually. WARR techniques are particularly useful for inferring propagation velocities in cases where the depth of the medium is unknown; however, in this study both the radar delay times and the 'ground truth' depths were recorded for a large number of sample points. Therefore, an empirical approach was adopted to determine an average propagation velocity for each deposit (Section 4.3). This provided more consistent results overall, and was used for the subsequent calculation of volume estimates. These values were also used to 'model' two of the WARR experiments; that is, to calculate the expected arrival times of the air, ground, and reflected waves at each measurement increment (Figure 4.6). It would appear that the WARR measurements were unreliable, since even the observed airwave arrival times were not always consistent with the known propagation velocity in air.

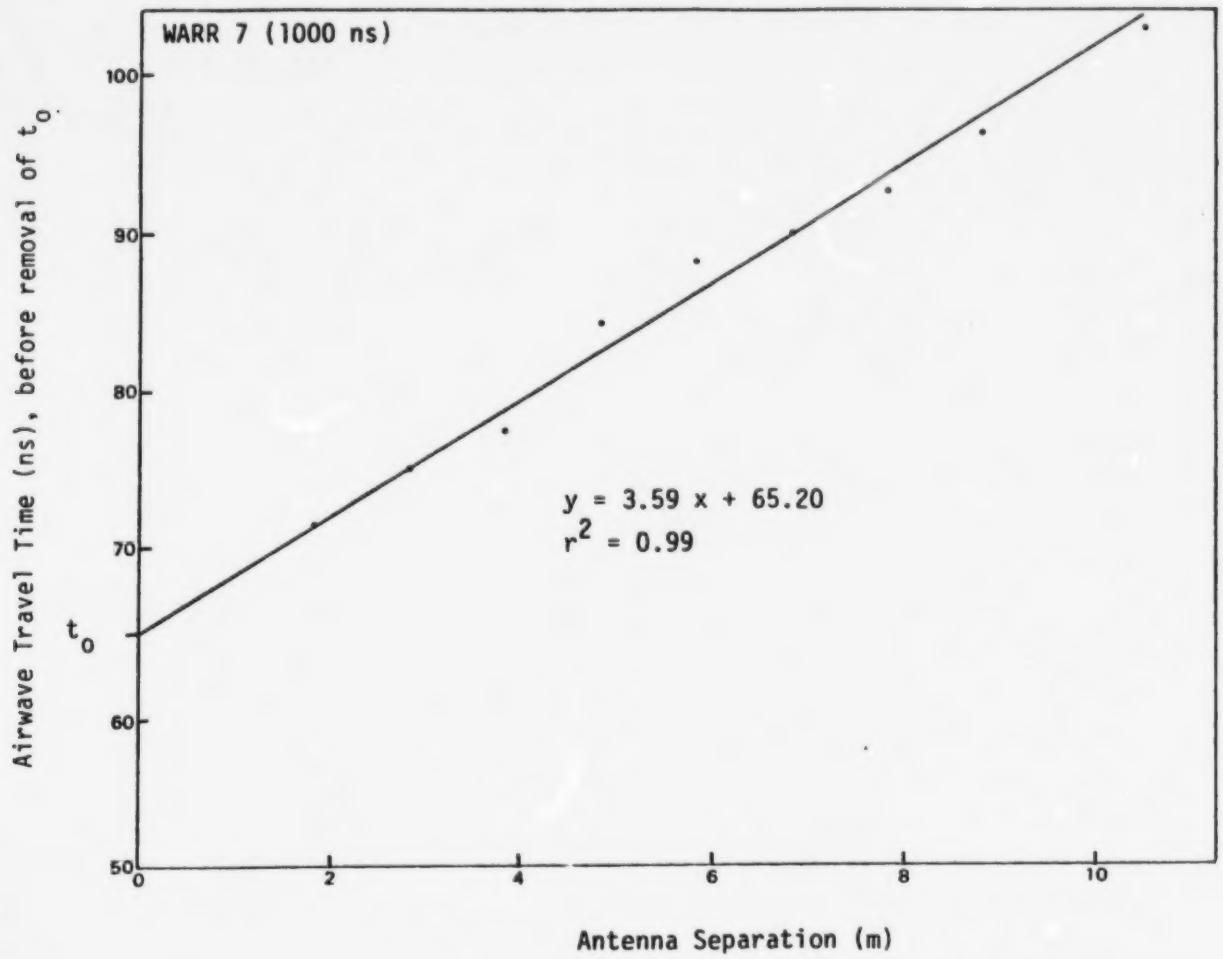


FIGURE 4.4 - GRAPH OF AIRWAVE TRAVEL TIME VERSUS ANTENNA SEPARATION - Linear regression yields t_o = 65.2 ns and speed of wave $c = 2.8 \times 10^8$ m/s.

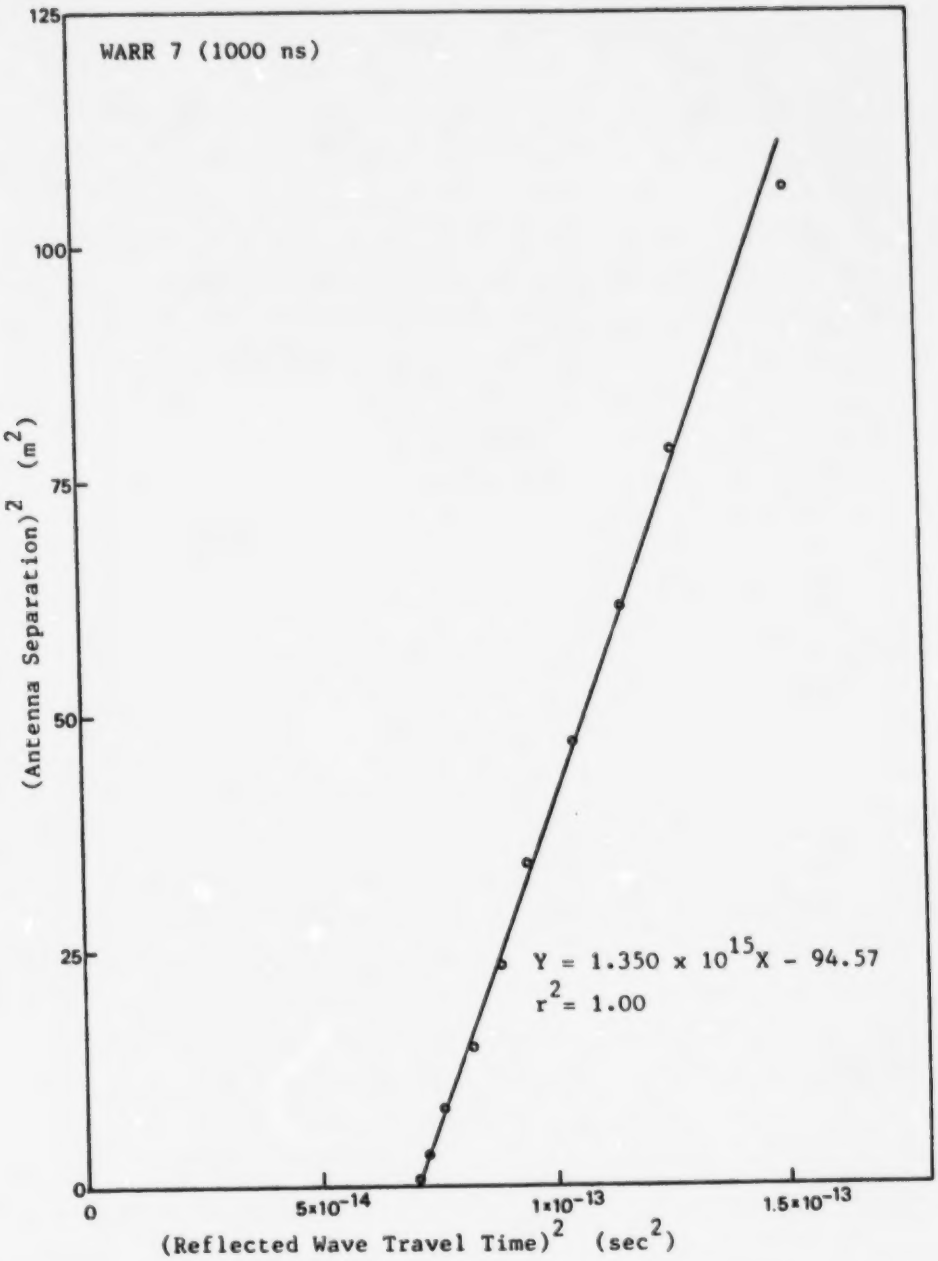


FIGURE 4.5 - GRAPH OF (ANTENNA SEPARATION)^2 VERSUS (REFLECTED WAVE TRAVEL TIME)^2

From the slope of the straight line fit to the data, the dielectric constant = 66.7 and propagation velocity = 0.037 m/ns. From the intercept, the depth at the WARR site = 4.86 m

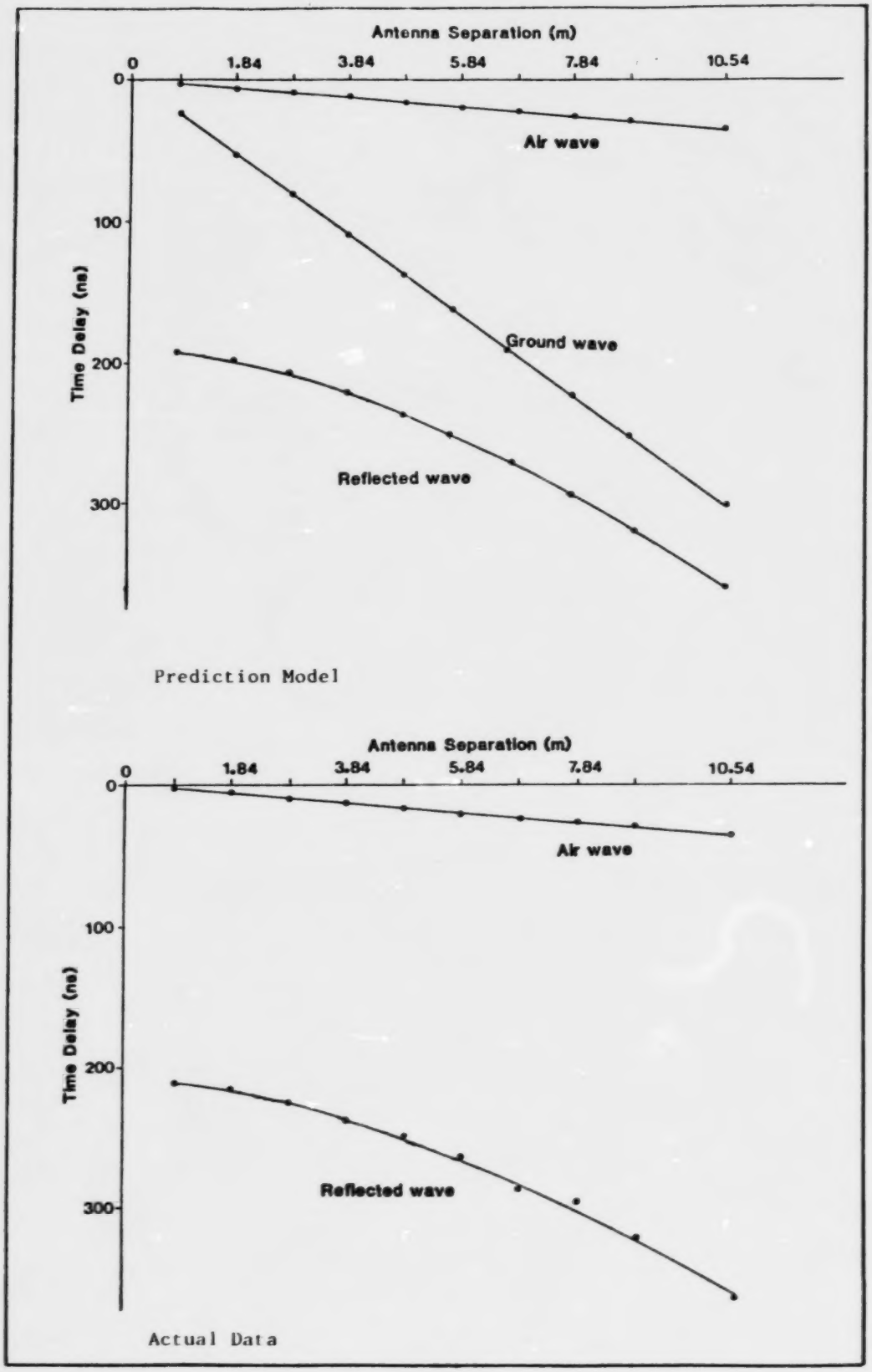


FIGURE 4.6 - WARR MODEL AND OBSERVED RESULTS

4.3 VELOCITY DETERMINATION

In order to calculate more reliable estimates of the radar propagation velocity and to allow a more rigorous statistical comparison of the different deposits, the 'ground truth' depths measured manually were plotted against the radar wave travel times scaled from the profile chart records. This was done separately for each deposit and for all deposits 'pooled' together. A regression line passing through the origin was then calculated for each set of data in the form:

$$y = b_o x \tag{4.1}$$

where y = peat depth
and x = the two-way travel (delay) time.

The slope, b_0, representing one-half of the actual propagation velocity, was calculated by:

$$b_o = \frac{\Sigma xy}{\Sigma x^2} \tag{4.2}$$

Although the regression line through the origin yielded slightly higher sums of squares of deviation (SSD) than would be obtained by a least squares fit, it is clear that barring any systematic measurement errors, the peat depth and the delay time must equal zero at the same point. With the equations in this form, it was possible to estimate the peat depths on the basis of the delay times, and compare these values with those observed manually. It should be noted that a regression line through the origin has one more degree of freedom than the least squares line for the same set of data (N-1 rather than N-2, where N = number of data points), since the mean x and y values are not used in calculating the equation.

The 'goodness of fit' of each regression was determined by calculating a correlation coefficient (r^2) where:

$$r^2 = \frac{b_0^2 \, \Sigma x^2 - \bar{y} \Sigma y}{\Sigma y^2 - \bar{y} \Sigma y} \qquad (4.3)$$

The standard deviation of the estimate (s $(\hat{y}_0)$) provided a measure of the average difference between the y-value predicted by the regression and that actually observed. This was calculated by:

$$s\,(\hat{y}_0) = \left| \frac{\Sigma y^2 - b_0 \Sigma xy}{N-1} \right|^{\frac{1}{2}} \qquad (4.4)$$

In turn, this value was used to calculate the standard deviation of any predicted value of y $(\hat{Y}_i)$ for a given x-value (x_i), using:

$$s\,(\hat{Y}_i) = s\,(\hat{y}_0) \left| 1 + \frac{1}{N} + \frac{x_i^2}{\Sigma x^2} \right|^{\frac{1}{2}} \qquad (4.5)$$

By selecting appropriate values from 't' tables at the desired level of probability, it was possible to establish confidence intervals around any depth predicted by a regression line.

The use of individual slopes (velocities) for each deposit gave lower total SSD's than the slope computed for the 'pooled' or composite data set. However, it would obviously be preferable for operational use if a single propagation velocity could be applied to all deposits. For this reason, an 'F' test was used to determine whether the individual slopes were significantly better than the composite slope. The F-value was calculated from:

$$F = \frac{(\Sigma y_c^2 - \Sigma\Sigma y_c^2) / (DF_c - DF_i)}{\Sigma\Sigma y_i^2 / DF_i} \qquad (4.6)$$

where Σy_c^2 = the SSD from the composite slope

$\Sigma\Sigma y_i^2$ = the sum of the SSD's from the individual deposit slopes

DF_c = the degrees of freedom for the composite data set

DF_i = the sum of the degrees of freedom for the individual data sets

This value was then compared with the critical F-value at 95 percent and 99 percent probability levels for the appropriate degrees of freedom.

Data from the first and second field programs was initially combined because of the small amount of data collected for any single deposit during the first program. Later, composite data sets for each program were compared, in order to evaluate seasonal differences. No 400 MHz data was included in this analysis because of the limited amount and poor quality of these profiles. Airborne data from profiles and from point soundings was analyzed, but was not included in the composite of ground-based data.

A description of the statistical procedures used is provided in Volk (1969).

4.4 VOLUME CALCULATIONS

A number of methods can be used to estimate the volume of a deposit once the peat depth has been determined at a number of known locations. In order to evaluate the relative accuracy of impulse radar techniques, a comparison was made between volume estimates based on manual measurements and those based on the radar profiles. The same method of volume calculation was used in all cases; the estimates differed only in terms of how the depth measurements were obtained and the spacing of the sample points.

Cross-sections of the deposits were drawn along each of the transect lines. The cross-sections were made up of a number of trapezoids, defined in x-direction by the horizontal distance between the sample points, and in the y-direction by the peat depths measured at those points (Figure 4.7). The cross-sectional areas were calculated by summing the areas of the individual trapezoids:

$$A = \sum \left\{ (x_{i+1} - x_i) \quad \frac{(y_{i+1} + y_i)}{2} \right\} \tag{4.7}$$

Where A = area of the cross-section

x_i = horizontal distance along transect line at sample point 'i'

y_i = depth measurement at sample point 'i'

The manual measurements were the depths recorded in the field at a fixed interval of 25 or 50 metres. The radar-derived depths were scaled from the surface to the bottom reflections on the chart records. Sample points were taken wherever significant breaks in slope were observed along the bottom profile. The two-way travel times were converted into units of depth using the individual deposit velocities and the composite propagation velocity, thus providing two sets of radar estimates. Once the cross-sectional areas had been calculated, the volume of material was estimated by:

$$V = \frac{A_i + A_j}{2} \quad x\ d \tag{4.8}$$

Where V = volume (in m^3)

A_i = cross-sectional area along line 'i' (in m^2)

A_j = cross-sectional area along line 'j' (in m^2)

d = distance between lines 'i' and 'j' (in m)

Point #	1	2	3	4	5	6	7	8	9	10
Distance (m)	0	43.3	85.3	91.1	115.2	158.9	207.6	271.6	321.9	348.9
Depth (m)	0.70	1.26	1.60	2.20	2.40	2.15	3.52	3.80	1.86	1.60

Trapezoid Areas (m^2)	42.43	60.06	11.02	55.43	99.43	138.06	234.24	142.35	46.71

FORT MOTEL BOG, Section A-A':

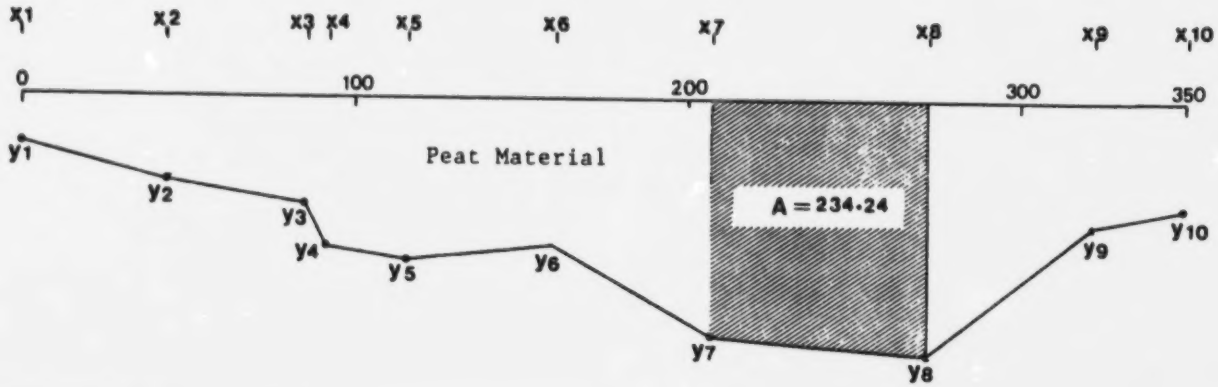


FIGURE 4.7 - CALCULATION OF CROSS-SECTIONAL AREA USING TRAPEZIODAL RULE.

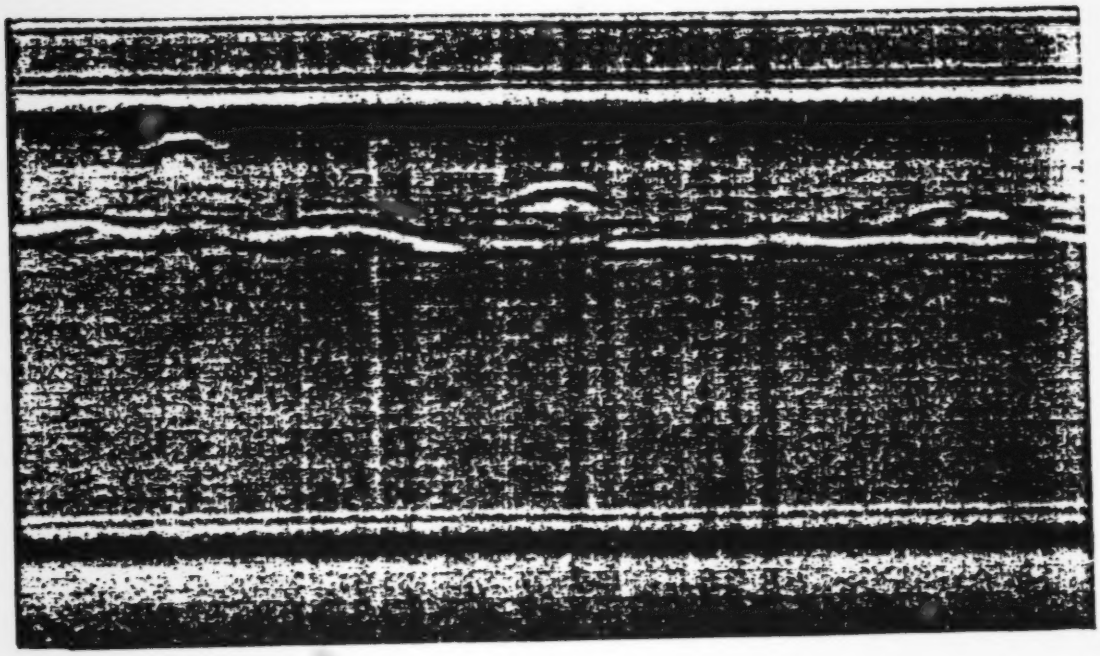
Volumes were calculated for the sampled portions of three deposits only; however, this was sufficient to allow a comparison of the measurement techniques.

4.5 DIGITAL ANALYSIS

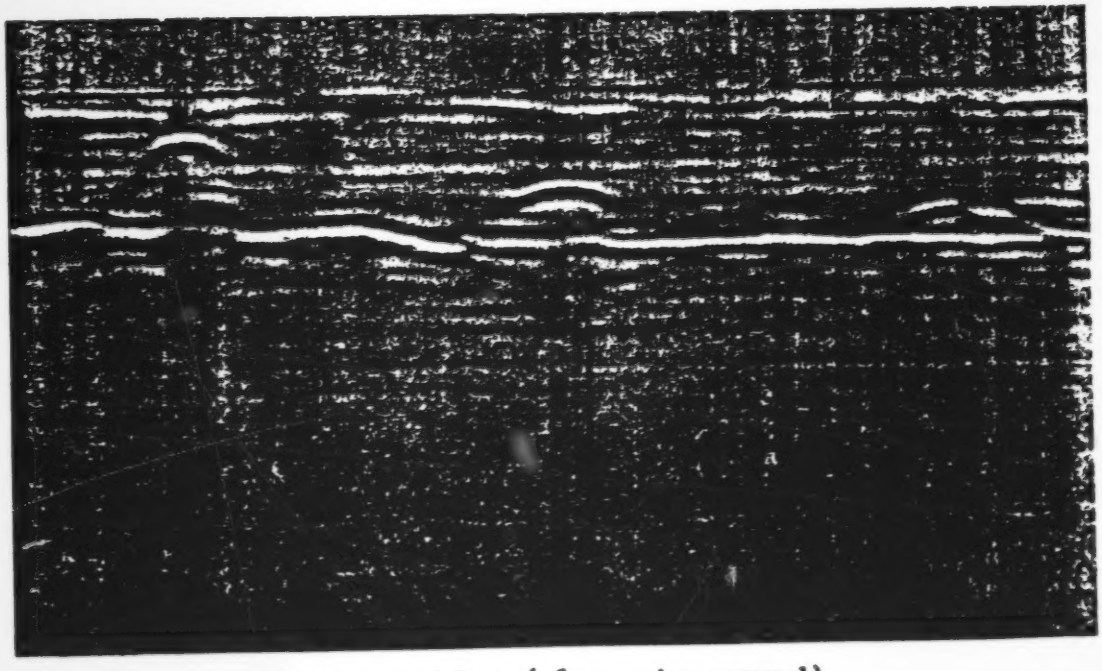
The primary objective of the digital analysis was to obtain an estimate of the radar signal loss in peat based on data from the attenuation experiment carried out at the High Point Bog. A secondary benefit was to demonstrate the feasibility of signal enhancement through the removal of large amplitude systematic noise.

The data was converted from an analog to a digital format using the Fourier Analyzer at Memorial University. The digitization was controlled by a clock signal recorded on the analog tape during the data collection; the sampling rate (1000 points per scan) was twice the recorded clock frequency. After digitization, the data was reformatted from a continuous stream into blocks of 1024 values, with each block consisting of 1000 data points and 24 zeros.

The first step in the data processing was the removal of systematic noise signals. Since the position of these signals was essentially constant throughout the record, this was accomplished by subtraction of an average noise signal based upon a sample of 50 scans. Initially, some difficulty was experienced in averaging the noise signals without also including the bottom reflections; however, this was eventually accomplished with a reasonable degree of success. Figure 4.8 (a and b) shows a plot of the radar profile before and after noise removal. Although only applied to the attenuation experiment, this enhancement technique should work equally well with other profile data.



A. Raw Data (before noise removal)



B. Processed Data (after noise removal)

FIGURE 4.8 - DIGITAL NOISE REMOVAL

The next stage of the processing involved the removal of the time varying gain (TVG) from the received signal levels. The gain settings on the GSSI control unit were not calibrated; however, by recording a calibrated input signal with the same gain settings used during the experiment and then digitizing this recording, the effect of the gain curve could be established (Figure 4.9). An array corresponding to the gain curve was stored in the computer and was used to correct each scan in the attenuation experiment data.

It was now possible to compare the signal levels obtained from the different reflectors within the peat. Each reflector signal consisted of a positive and a negative peak. The amplitudes of these peaks (voltage) were plotted as a function of distance (twice the reflector depth measured in the field) and were fitted by an exponential least squares curve having the general form:

$$y = a.e^{-bx} \qquad (4.9)$$

where y = voltage
and x = distance travelled

However, since attenuation is normally expressed as a power loss, and power equals voltage squared, then:

$$y^2 = a^2.e^{-2bx} \qquad (4.10)$$

Therefore, the x-coefficient (2b) represents the attenuation coefficient of power in nepers per metre. This can be converted to decibels per metre by multiplying the value by 4.34.

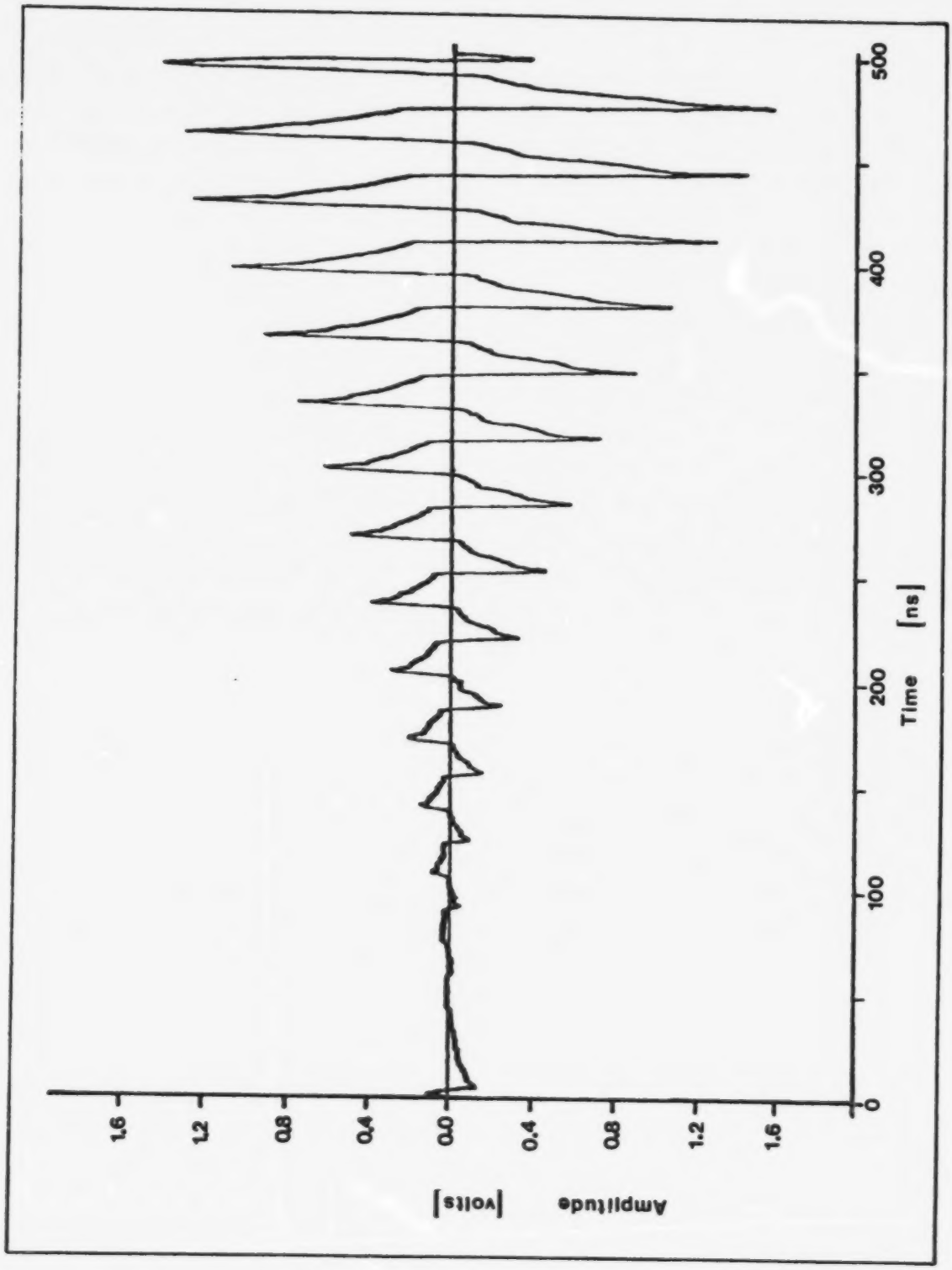


FIGURE 4.9 - CALIBRATED SIGNAL SHOWING APPLIED GAIN

4.6 PEAT SAMPLE ANALYSIS

Peat samples collected from the study deposits were taken for analysis to the Physical and Chemical Analysis Laboratory at the Newfoundland Forest Research Centre. Five parameters were analyzed for each sample: type of parent material; degree of humification (Von Post number); bulk density; percent moisture content; and electrical conductivity. Although a Von Post number was estimated in the field, this measurement is a subjective one, and it was felt that the experience of the NFRC technicians would provide a more reliable assessment. The bulk density measurements may have been affected by the method of storage (in loose form in plastic bags); however, no facilities were available to preserve the cores intact. The electrical conductivity was measured on water expressed from the peat samples, either "as received" or diluted (with appropriate corrections to the measurements).

As explained in Section 3.3, the objectives of the sample collection and analysis were revised between the first and second field programs. The parameters tested remained the same in both cases, however. After the analysis results were received from the first program, they were evaluated to see how the various parameters differed within and between deposits. It appeared that all of the deposits were more or less equally heterogeneous with respect to their peat characteristics, based on the small number of samples taken from each. In order to determine whether the layering observed in the Whitbourne Bog corresponded to physical changes in the peat, the analysis results were plotted as a function of depth at each sample point, and were then compared with the internal interfaces apparent on the profile records.

CHAPTER 5

RESULTS AND DISCUSSION

5.1 DIELECTRIC CONSTANTS AND PROPAGATION VELOCITIES

Nine of the ten WARR experiments yielded a sufficient amount of data for analysis (i.e. recognizable reflected wave returns). The sole exception was the 400 MHz WARR, for which there were not enough data points, presumably due to poor signal penetration (high attenuation) at this frequency. Some of the 80 MHz data was ambiguous, however. Three of the WARR records indicated two reflected wave signals and it was assumed that the signals with the longer time delay were the true bottom reflections. Subsequent "modelling" of these WARRs indicated that these earlier waves were not ground waves, (unless somehow refracted), and they were probably reflections from internal peat interfaces. One WARR also showed a significant discrepancy between the time delays measured on the visicorder record and those measured on the scope photographs.

The WARR results are summarized in Table 5.1 (the graphs from which these values were derived are presented in Appendix "C"). The dielectric constants obtained from the nine WARRs ranged from a low value of 51.4 to a high of 69.99. There was a considerable difference between some of the depths obtained from the WARR graphs and those measured manually. This difference was most pronounced where the actual peat depth was relatively shallow, and was least at the deeper peat sites.

The regression analysis of 'ground truth' depths and radar delay times produced more consistent results. Table 5.2 presents the results obtained for the individual deposits and the composite data set (ground-based data only). The slope values (b_o) are equal to one-half of the one-way propagation velocity in metres per nanosecond, and were used to calculate the dielectric constants. These varied from 60.8 (for

WARR No.	Location	Date	Dielectric Constant	Propagation Velocity	Depth from WARR graph	'Ground Truth' Depth
1	Whitbourne Bog	21/07/81	65.6	.037m/ns	2.66m	3.6m
2	Witless Bay Bog	31/07/81	51.4	.042m/ns	4.13m	1.8m
3*	Witless Bay Bog	01/08/81	----	-------	----	----
4	Fort Motel Bog	01/08/81	69.5	.036m/ns	3.78m	3.3m
5	High Point Bog	04/08/81	55.6	.040m/ns	4.26m	1.5m
6	Whitbourne Bog	05/08/81	70.0	.036m/ns	3.92m	3.9m
7	Whitbourne Bog	01/09/81	66.7	.037m/ns	4.86m	4.9m
8	Fort Motel Bog	05/09/81	62.2	.038m/ns	4.00m	3.4m
9	High Point Bog	21/10/81	53.6	.041m/ns	4.25m	1.5m
10	High Point Bog	22/10/81	66.4	.037m/ns	7.18m	7.0m

* 400 MHz - insufficient data for analysis

TABLE 5.1 - SUMMARY OF WARR RESULTS

Deposit	Number of Data Points	Depth (m)		Slope	Correlation Coefficient	Dielectric Constant	Standard Deviation of the estimate	Standard Deviation of predicted value $s(\hat{Y}_i)$	
	n	min	max	b_o	r^2	ϵ	$s(\hat{y}_o)$	50ns	400ns
Fort Motel Bog	27	0.65	4.00	0.01842	0.965	66.3	0.185	0.189	0.213
Witless Bay Bog	49	0.30	2.00	0.01924	0.967	60.8	0.091	0.093	0.122
Whitbourne Bog	38	1.90	4.95	0.01788	0.912	70.4	0.242	0.245	0.256
High Point Bog	42	1.25	7.00	0.01809	0.997	68.8	0.129	0.130	0.133
Johathan's Pond Bog	7	5.60	7.95	0.01793	0.993	70.0	0.067	0.072	0.076
Composite (all bogs)	163	0.30	7.95	0.01808	0.994	68.8	0.168	0.169	0.171

TABLE 5.2 - RESULTS OF REGRESSION ANALYSIS

the Witless Bay Bog) to 70.4 (for the Whitbourne Bog), while the composite value was 68.8. The standard deviation of the estimate ($s(\hat{y}_0)$) provides a measure of the average difference (in metres) between the manually measured depths and those predicted by the regression equations. The significance of these values is open to interpretation, however. On the one hand they might be taken to suggest that the radar propagation velocity varies proportionally to these values within each deposit. But as discussed in Section 5.5, manual measurements themselves are variable within a relatively small area. Although insufficient data was collected to quantitatively evaluate the effects of small-scale depth variations or manual measurement errors for each deposit, the limited amount of testing which was done suggests that a large part of the variance observed could be attributable to these factors. Furthermore, if velocity variations within deposits were large, the standard deviation of the estimate would presumably be higher for greater peat depths. This in fact was not observed, from which it may be assumed that the propagation velocity was relatively constant, at least within the deeper deposits.

The F-test was used to determine whether the slopes calculated individually for each deposit were significantly different. The result indicated that the increase in SSD values using the composite slope was significant, both at the 95 and 99 percent probability levels. This would seem to imply that a separate propagation velocity should be used for every deposit. However, when the data from the Witless Bay Bog was excluded and the F-test was repeated, it was found that the remaining slopes were not significantly different, even at 95 percent probability. It would appear, therefore, that the composite velocity is a reliable predictor for at least four of the five deposits.

Because the Witless Bay Bog is relatively shallow, the differences in the depth values predicted by the individual and composite slopes were small (in absolute terms), and the difference in the propagation velocity for this deposit was not apparent until after the

second field program. If the slope calculated for the Witless Bay Bog is reliable, and representative of deposits elsewhere, the magnitude of the prediction error associated with the composite slope would increase with depth. It may still be acceptable to use a composite velocity for such deposits, however, depending upon their depth and the degree of accuracy required. In Table 5.2, the standard deviation of any predicted value ($s(\hat{Y}_i)$) has been given for 50 and 400 nanosecond delay times. By multiplying these figures by the 't' values for the proper degrees of freedom and desired probability levels, confidence limits can be established around the depth predictions for each slope. At 50 nanoseconds, for example, the Witless Bay slope gives a peat depth of 0.962 metres, while the composite slope predicts a depth of 0.904 metres. The 50 percent confidence interval for the composite prediction is $\pm$ 0.114 metres, which encompasses the 'true' value. At 400 nanoseconds, it is necessary to go to a 99.9 percent confidence interval for the composite prediction (7.232 $\pm$ 0.564 metres) to include the 'true' value (7.696 metres). It should be noted that while the absolute error of the prediction (using the composite slope) does increase with depth, the relative error remains constant; in this case about 6 percent. For certain applications, this may be quite satisfactory, and a single propagation velocity could be used for all deposits.

Figure 5.1 shows the plot of the composite ground-based data set. The individual deposit graphs are included as Appendix "D". Delay times measured from the airborne profiles and from the helicopter set-down tests (point measurements) are presented in Figures 5.2 and 5.3 respectively. Although the slopes of these regressions differ significantly from the ground-based slopes, this is probably the result of offsets away from the sample points. This is especially true for the airborne profile data, as evidenced by the relatively low correlation (r^2 = 0.781). It is unlikely that the deployment of the radar system from an airborne platform would affect the radar propagation velocity within the peat. However, it is clear that track recovery could be a problem for operational airborne profiling.

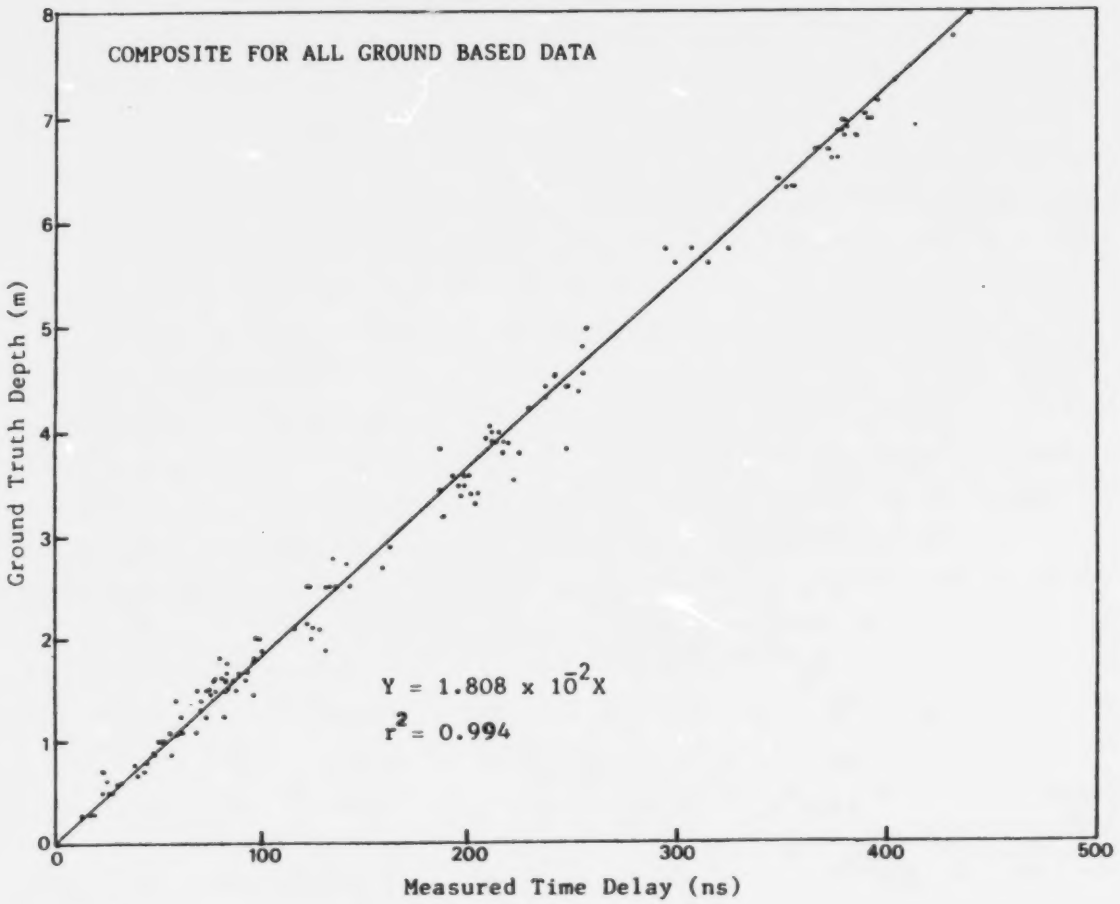


FIGURE 5.1 - GRAPH OF GROUND TRUTH DEPTH VERSUS MEASURED TIME DELAY

From the slope of the straight line through the origin, the dielectric constant = 68.8 and the propagation velocity = 0.036 m/ns

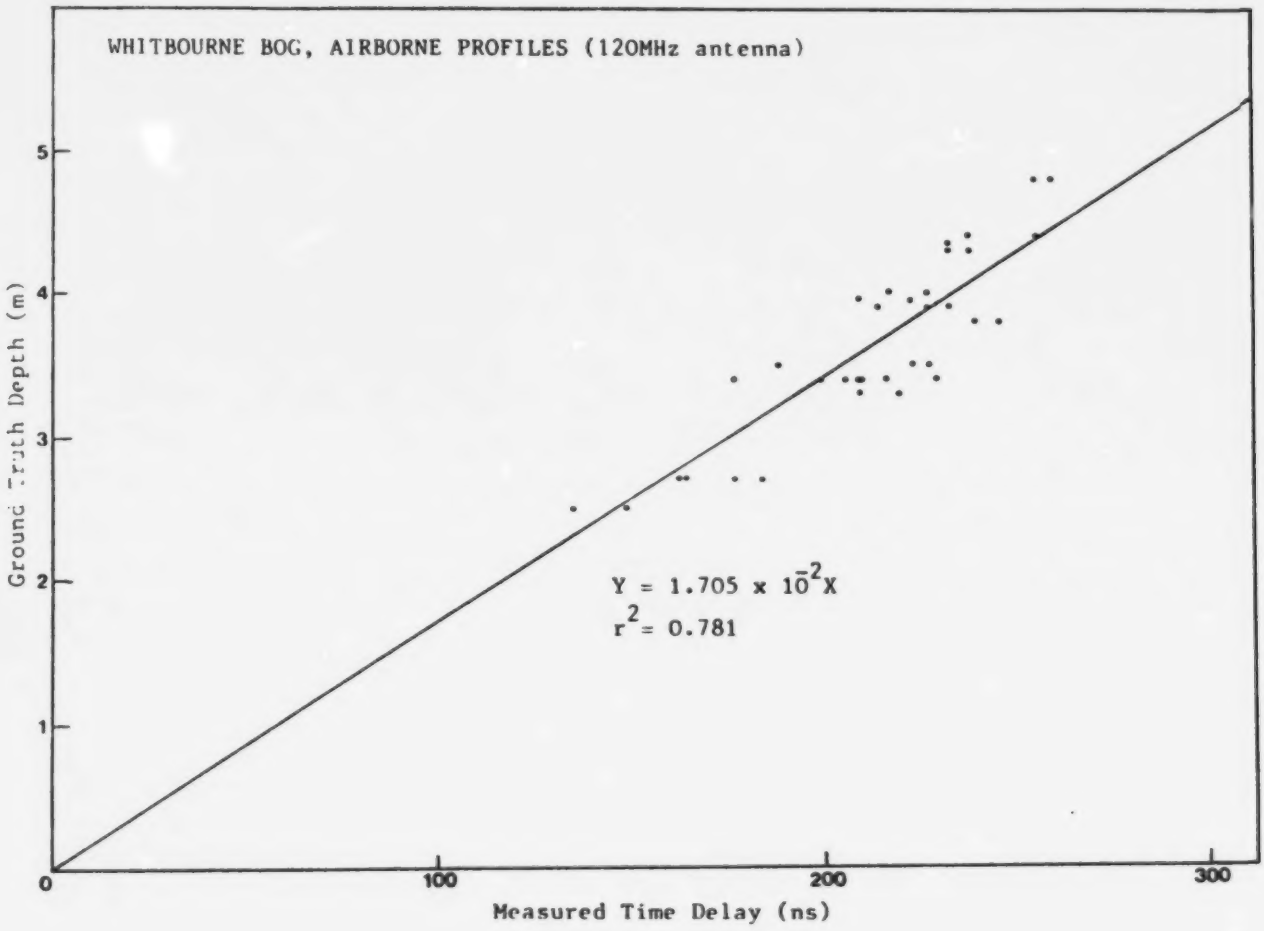


FIGURE 5.2 - GRAPH OF GROUND TRUTH DEPTH VERSUS MEASURED TIME DELAY

From the slope of the straight line through the origin, the dielectric constant = 77.4 and the propagation velocity = 0.034 m/ns.

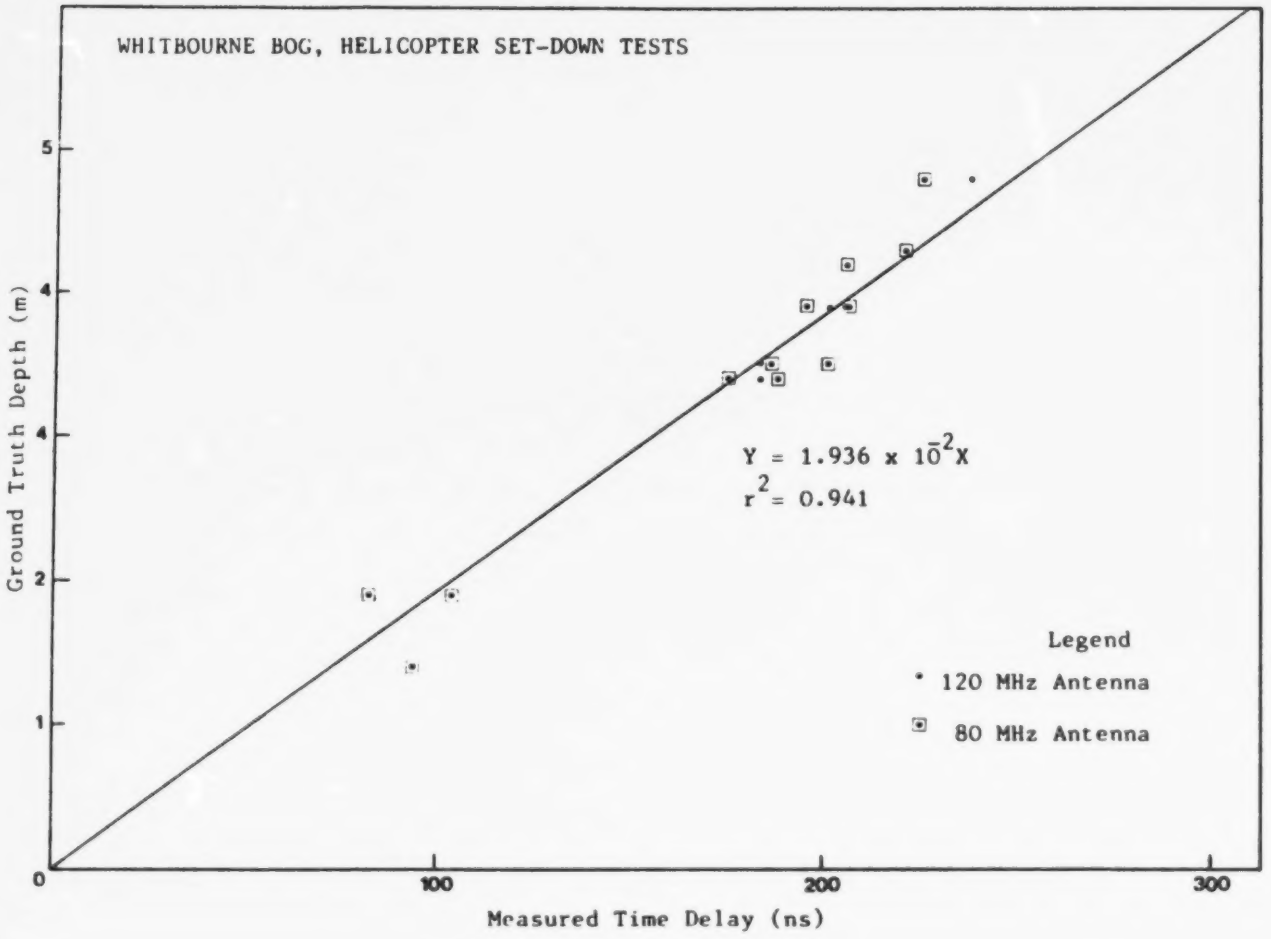


FIGURE 5.3 - GRAPH OF GROUND TRUTH DEPTH VERSUS MEASURED TIME DELAY

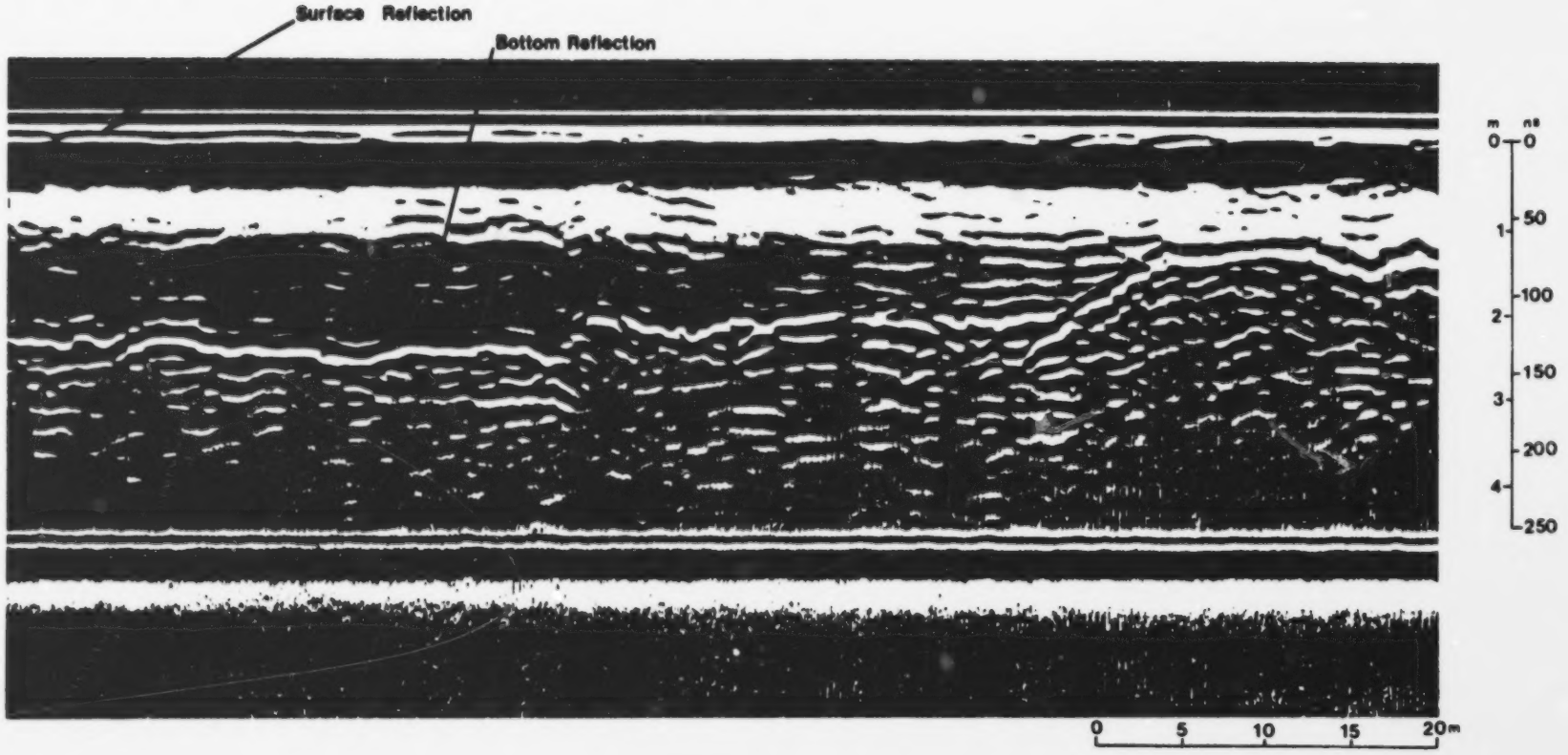
From the slope of the straight line through the origin, the dielectric constant = 60.0 and the propagation velocity = 0.039 m/ns

5.2 SYSTEM PERFORMANCE

The 80 MHz antenna, operated in a ground-based mode, yielded the clearest and most consistent deposit bottom profiles. Depths ranging from 0.75 to 8.1 metres were measured with this system and it would appear that greater penetration should be possible. Relatively little systematic noise was evident on the 80 MHz profile records, with the exception of one particularly distinct noise band which seldom interfered with the bottom return. Random noise signals, though present, were not clearly noticeable except at the higher gain settings required for depths greater than 7 metres. Figure 5.4 shows a typical 80 MHz profile.

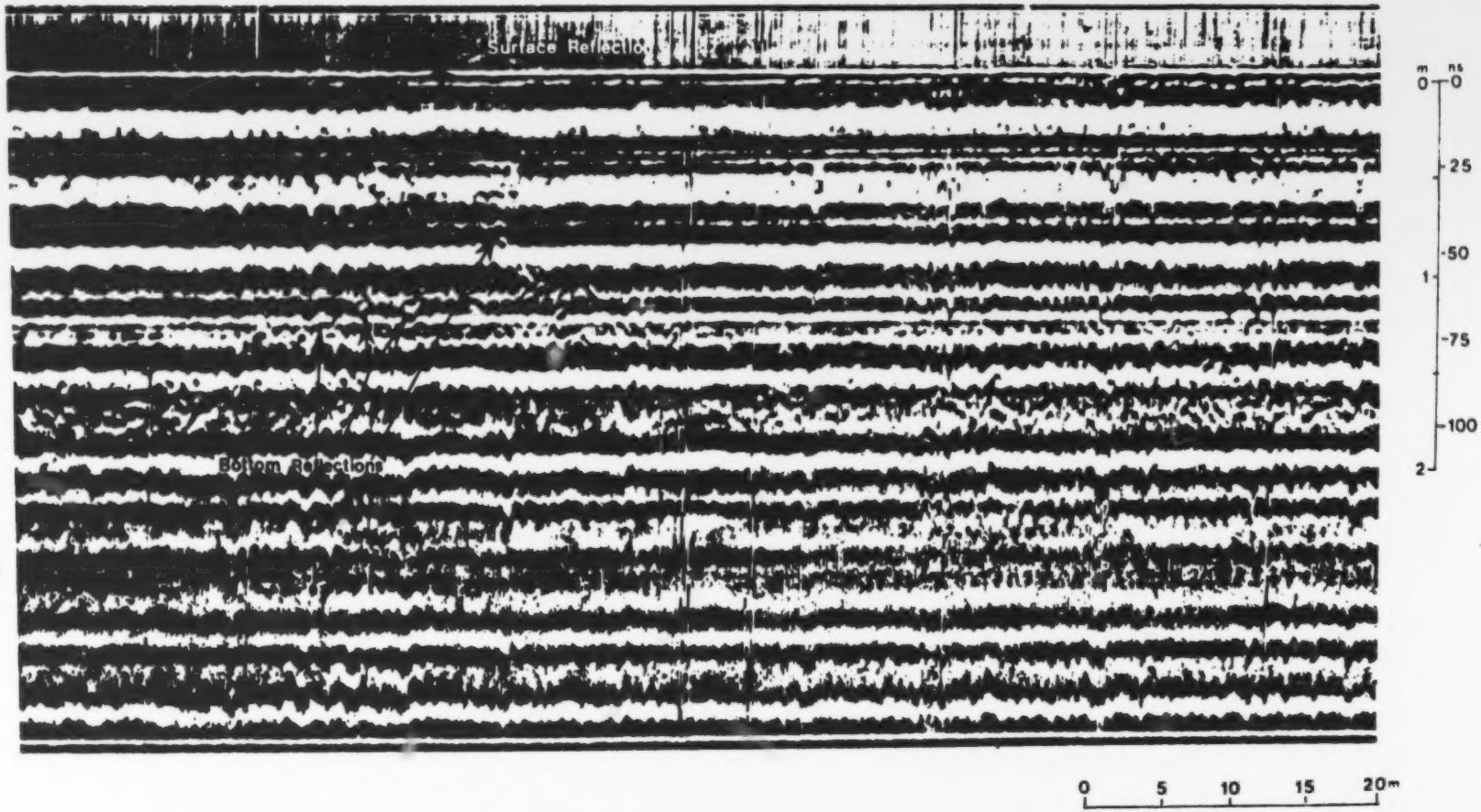
The 400 MHz data was much poorer in quality (Figure 5.5). These profile records were dominated by strong bands of systematic noise and "spikes" from random noise effects. Bottom reflections from 0.4 to 2.0 metres were detected, but were weak and intermittent. In fact, the maximum gain settings had to be used in order to detect these returns, which is believed to be the cause of most of the noise problems. The fact that the 400 MHz system was operated in a bistatic configuration for profiling (as opposed to the monostatic operation of the 80 MHz system) did not appear to have been significant in contributing to the poorer quality of the data, based on a comparison of equivalent WARR measurements.

Airborne profile data was collected with both an 80 MHz and a 120 MHz antenna. Similar results were obtained with both frequencies, although systematic noise bands were more pronounced on the 120 MHz data (Figure 5.6). Returns from the deposit bottoms were not strong and were at times intermittent, although they were generally distinguishable from the background noise. Random noise spikes were significant with both systems, due to the high gain settings required. An additional source of noise in the airborne data was radio frequency interference (caused by television or FM radio transmissions, weather radar, etc.) which was most noticable over the Fort Motel Bog, the closest deposit to St. John's. The



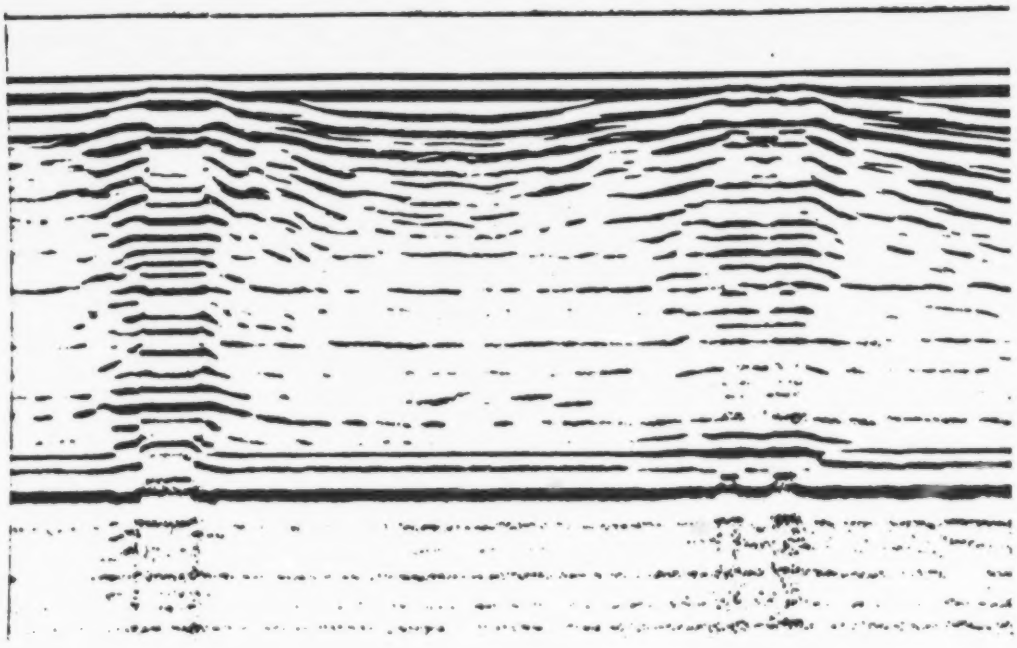
Partial profile from Section A-A', Fort Motel Bog.

FIGURE 5.4 - TYPICAL GROUND BASED DATA, 80 MHz SYSTEM

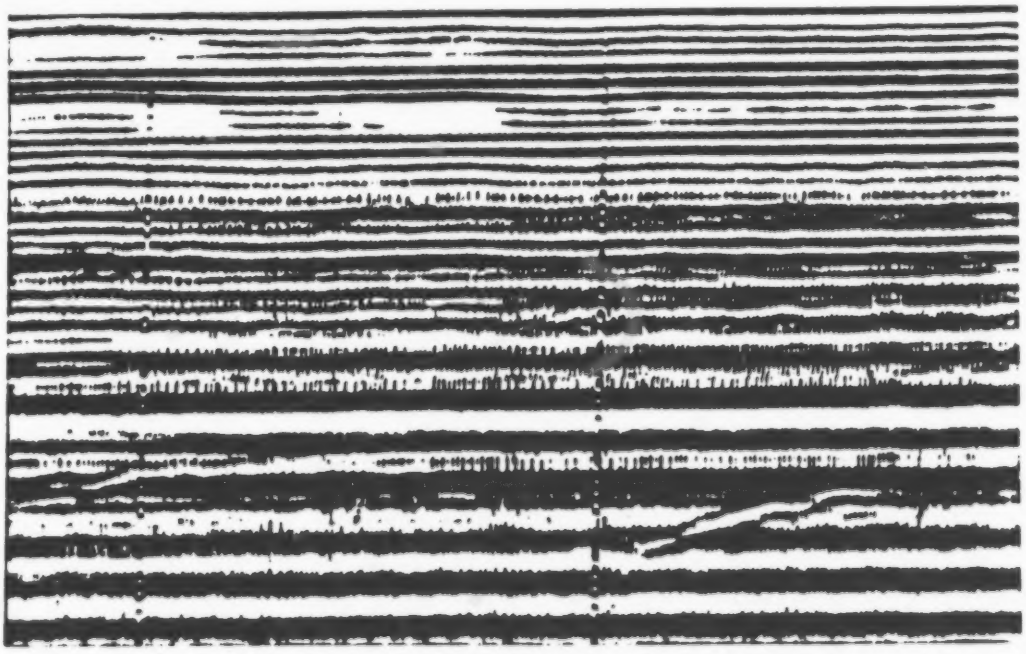


Partial profile from Section B-B', Witless Bay Bog

FIGURE 5. 5 - TYPICAL GROUND BASED DATA, 400 MHz SYSTEM



A. Example of data from the 80 MHz system for airborne profiles and set down tests



B. Example of data from the 120 MHz system for an airborne profile

FIGURE 5.6 - TYPICAL AIRBORNE DATA

effect of this interference was minor, due to the low altitudes used for profiling, but it may have limited the amount of gain which could be applied in some instances. Deposits of up to 4.8 metres were successfully profiled, which was the maximum depth over which airborne data was acquired.

The point measurements made with the helicopter set down on the deposit surface showed very strong bottom returns comparable with those obtained on the ground-based profiles. The strength of these reflections diminished rapidly as the the helicopter rose vertically, and became indistinguishable at altitudes greater than 2 metres. This upper limit was also confirmed when the 80 MHz antenna was raised manually during ground-based tests. It would seem that when the antenna is in direct contact with the surface, it is effectively coupled to the medium, and little energy is lost at the air/peat interface. At distances of up to 2 metres, this interface remains within the "near field" of the antenna, and profiling is still possible. Beyond the near field, however, the surface interface reflects most of energy and the remainder which does penetrate into the peat is too weak to reflect from the deposit bottom back to the receiver.

5.3 ATTENUATION RESULTS

The voltage levels received from the reflectors (after noise and gain removal) were plotted as a function of the distance travelled by the radar wave (Figure 5.7). The exponential least squares curve fitted to these points was:

$$y = 6.61\ e^{-1.00x}$$

for which the power equivalent was:

$$y^2 = 43.7\ e^{-2.01x}$$

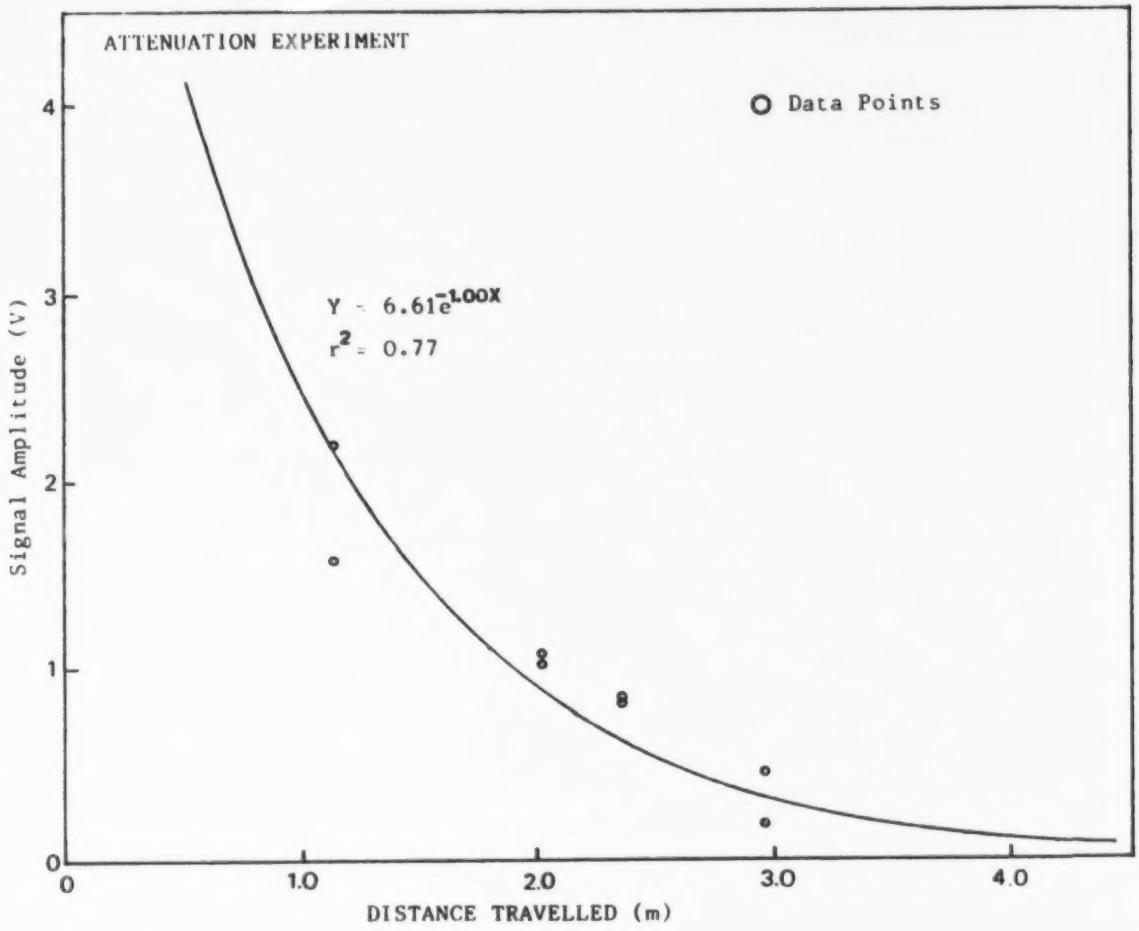


FIGURE 5.7 - GRAPH OF SIGNAL AMPLITUDE VERSUS DISTANCE TRAVELLED

Note that the "distance travelled" by the radar signal is twice the depth of the reflector.

The x-coefficient, -2.01, represents the attenuation in nepers per meter, which may also be expressed as 8.72 decibels per metre. This value is extremely close to the attenuation for peat (at 80 MHz) reported by Bogorodskii and Trepov (1979) of 8.8 decibels per metre. These researchers also reported that attenuation increased sharply with increasing centre frequency.

In this representation of the voltage data, spreading losses were not taken into account. The loss in voltage would be inversely proportional to the distance travelled, assuming a point source approximation where the antenna size is small compared with the distance to the target. During the attenuation experiment, however, the antenna size and the distance to the target were of the same order of magnitude. Spreading loss calculations based on the actual antenna size and shape were not attempted.

The removal of the systematic noise and the time varying gain may have introduced some errors into the attenuation data. The noise removal program could have increased the scatter of the data points, but should not have affected the "best-fit" curve in any systematic manner. During the gain removal, however, no attempt was made to gauge the stability or the accuracy of the TVG. If there were significant variations in the TVG during the attenuation experiment, the adjusted voltage levels would be incorrect.

5.4 LAYERING

Some indication of internal layering was evident on most of the deposit profile records. These layers appeared to be actual interfaces, rather than echos of the surface or bottom reflections. In most cases the layering was intermittent and varied in strength from one deposit to another. However, the location and shape of the layers remained consistent for transect lines profiled during two different field programs.

In order to determine whether the reflecting interfaces corresponded to changes in the physical characteristics of the peat, a 25 metre section of one transect line on the Whitborne Bog was studied in detail. Figure 5.8 (a) and (b) shows the profile record, together with the interpreted interface depths at the 5 metre sample intervals. The analysis results from the peat samples collected at these intervals are presented in Figure 5.9 (a) to (e).

No single parameter or combination of parameters provided a consistent correlation with the observed layering. A thin layer of woody peat showed up clearly, but was not noticably different from the other interfaces. Several layers corresponded with marked changes in bulk density and/or conductivity, yet other equally large variations in these parameters did not stand out at all. In some cases, there did not appear to be a relationship between the interfaces and any of the measured parameters.

The method of sample collection and storage was not ideal for analysis purposes. Samples were obtained from 25 or 50 centimetre sections through the peat, depending whether visible differences were observed in the peat characteristics. For the 25 centimetre sections, two or more adjacent cores had to be combined in order to yield sufficient material for analysis. The woody peat layer was too thin to obtain an analyzable sample. In addition, there were no facilities for storing core samples intact, which may have had an effect on the bulk density measurements.

The complexity of this peat cross-section, indicated by the analysis results, made the delineation of well defined layers almost impossible on the basis of any of the measured parameters. It is therefore difficult to assess the utilty of impulse radar for providing information on the internal structure of the deposit. The layering observed on some of the profile records from other deposits indicated a simpler formation, although the interface returns were not as strong as

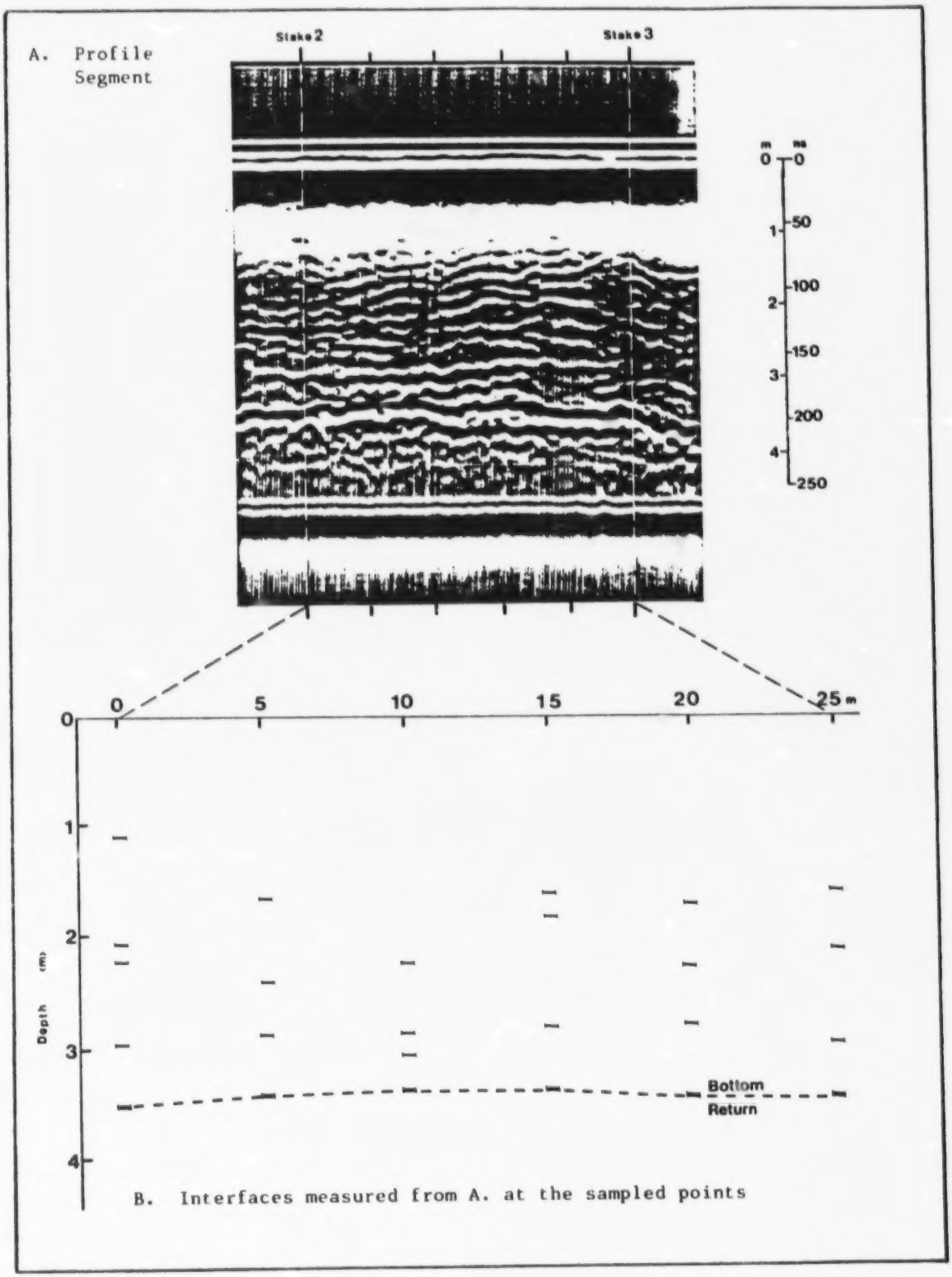


FIGURE 5.8 - LAYERING OBSERVED IN WHITBOURNE BOG

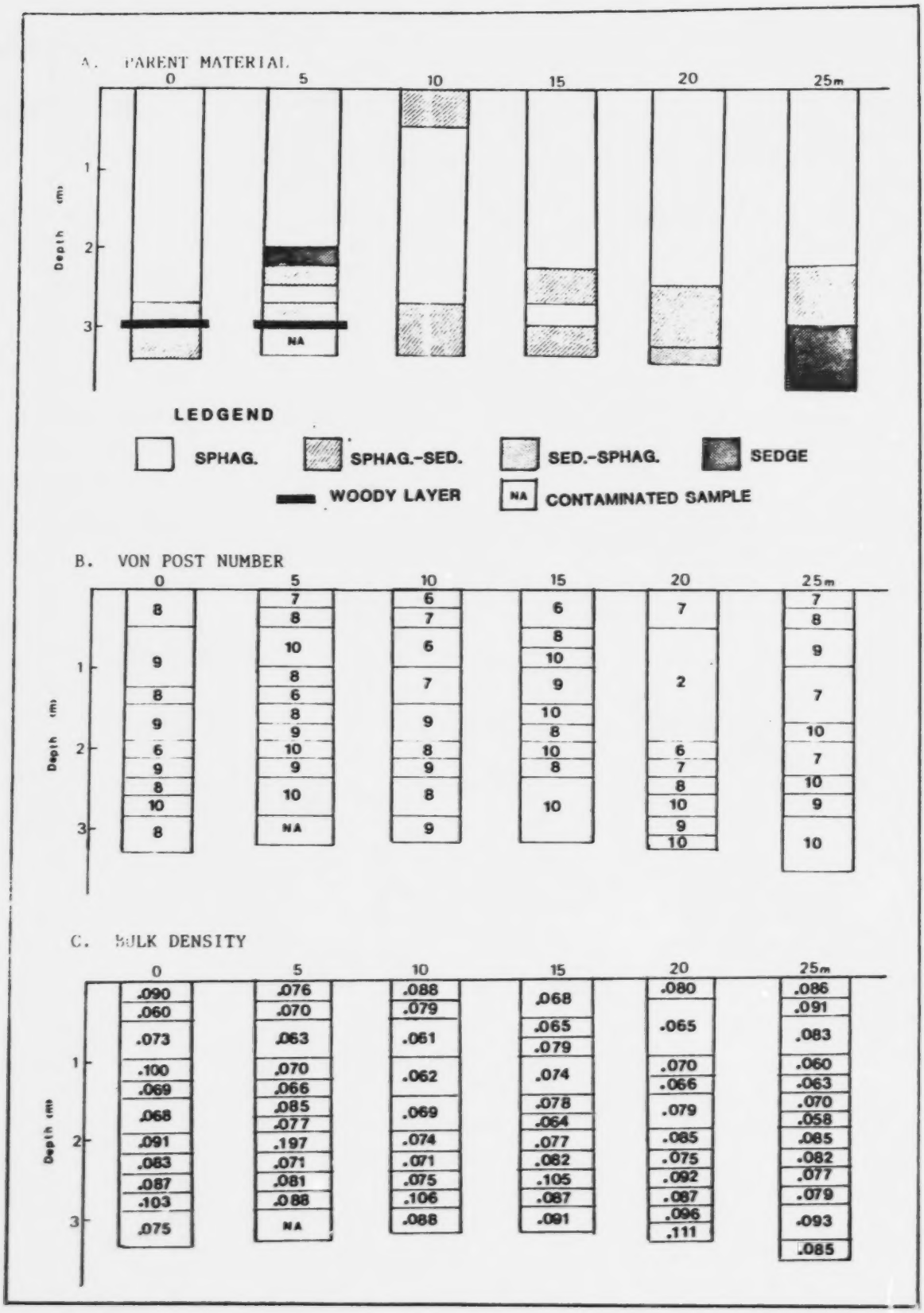


FIGURE 5.9 - RESULTS OF INTENSIVE SAMPLING (Whitbourne Bog)

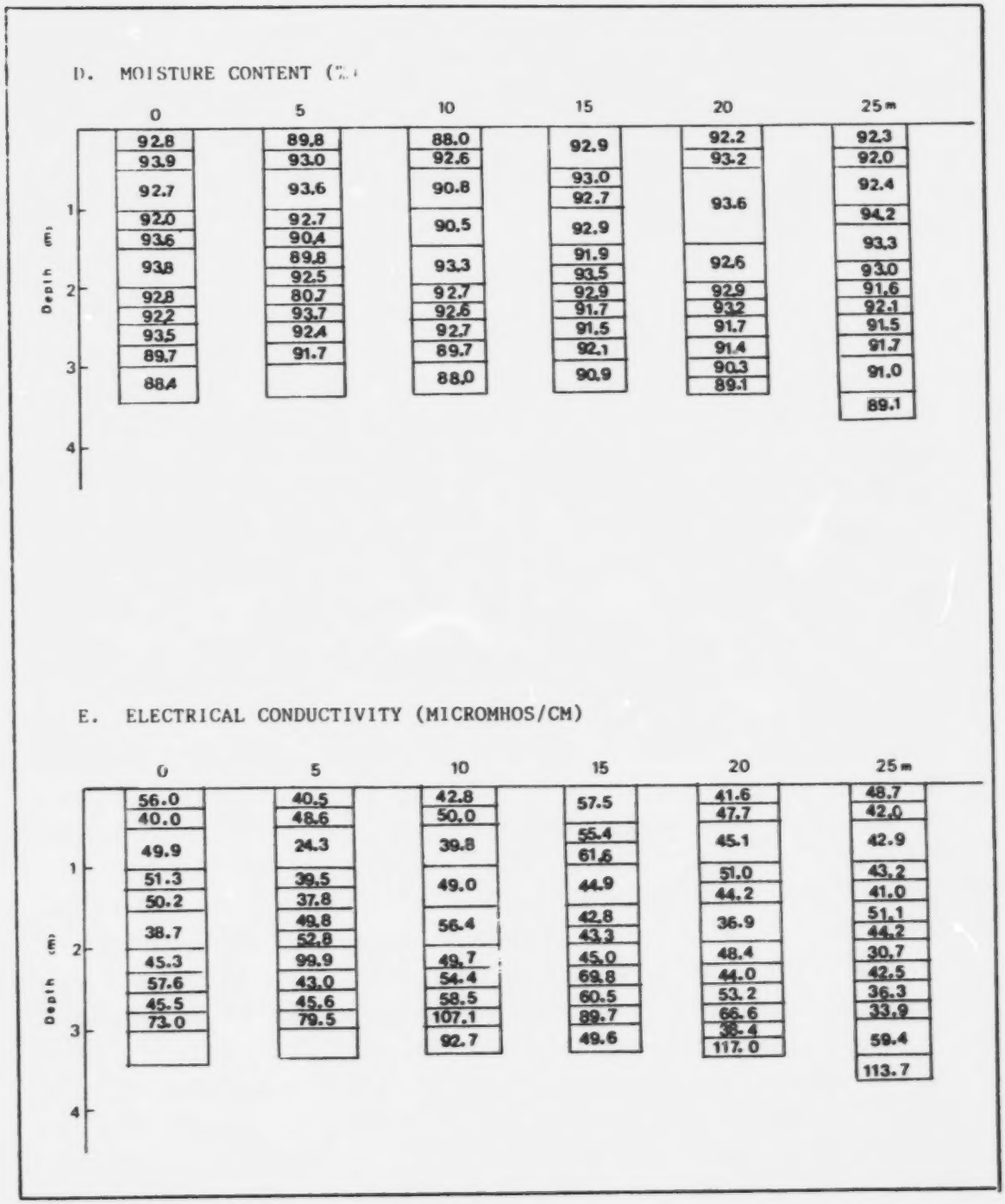


FIGURE 5.9 (continued) - RESULTS OF INTENSIVE SAMPLING (Whitbourne Bog)

for the Whitbourne Bog. Although further data collection and analysis is needed before drawing any definite conclusions, it would appear to be unlikely that impulse radar data alone can adequately describe any of the physical or chemical properties of peat. It may be possible, however, to interpolate layers between manually sampled points, providing that the discontinuities are not too complex.

5.5 DEPTH MEASUREMENTS AND VOLUME ESTIMATES

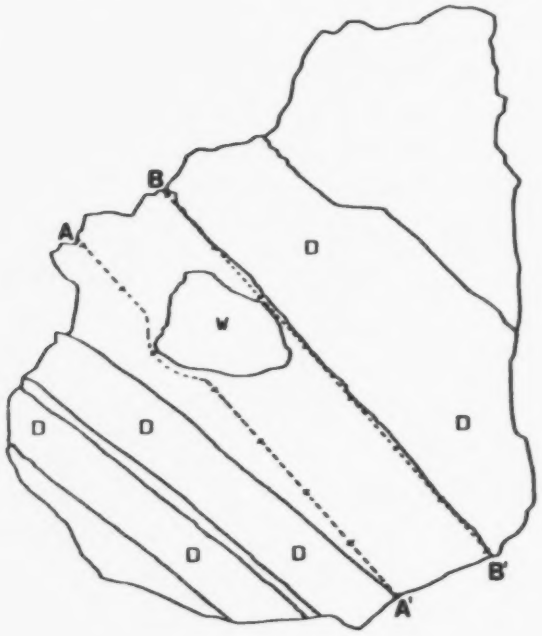
Depths measured manually with the Hillier sampler and radar-derived depth for the same sample points showed a difference ranging from 0 to 50 centimetres, using both the composite and individual deposit propagation velocities. On average, the differences were within $\pm$ 15 centimetres. Although the manual measurements were taken as the 'ground truth' values for the purpose of regression, it was clear that they contained a certain margin of error or uncertainty. Potential causes of this uncertainty included non-vertical sounding, irregularities in the deposit bottom, and visual "rounding off" of the sampler depth. As described in Section 3.3, a series of manual measurements (on average 30) were taken within a one square metre area around a limited number of sample points. These depths varied by up to 30 centimetres at one point to as much as 50 centimetres in the most extreme case. There was no apparent correspondence between the amount of variation in the manual measurements and the total peat depth, suggesting that bottom roughness was the major factor affecting variability. Since the bottom reflections observed on the radar profiles were in fact composite returns from the 'footprint' area of the radar, the time delays which were measured may be considered as "averaged" values. It seems probable, therefore, that most of the discrepancies between manual and radar-derived values could be attributed to this cause. Variations in bottom roughness presumably differed from one deposit to another depending on the nature of the underlying material which would account for the difference in the average estimate error calculated for each deposit.

Cross-sectional areas and partial deposit volumes were calculated for three of the study deposits (Figure 5.10 to 5.12). Three sets of estimates were prepared in each case: one based on manual depth measurements, and two based on radar derived depths, using the individual and composite propagation velocities (Table 5.3). In all but one case, the different data sets yielded volume estimates which agreed within 5 percent. The difference between the manual depth estimate and the composite radar velocity estimate for the Witless Bay Bog was approximately 10 percent, but was actually quite small in terms of the amount of material. Examination of the cross-sections in Figure 5.11 indicates that because of the sampling interval used, the manual estimate may have been somewhat high. By providing continuous profiles rather than point data, the impulse radar record gives a more detailed portrayal of the deposit bottom than manual measurements. This could be particularly useful in planning the extraction of peat from a deposit.

Without an independent means of determining the 'true' peat depth or deposit volumes, it is difficult to evaluate the relative accuracies of manual and radar-based estimates. It would be necessary to take a series of manual depth measurements around every sample point, and calculate the mean and standard deviation values, in order to quantify the actual variability of the radar velocity within each deposit. This would entail considerable time and effort; for the purpose of this study it was considered sufficient to demonstrate that both techniques yielded comparable results. Based on the data selected, it appears that use of a composite velocity is justified in most cases, while individual deposit velocities should be used where absolute accuracy must be maximized.

5.6 SEASONAL VARIATIONS

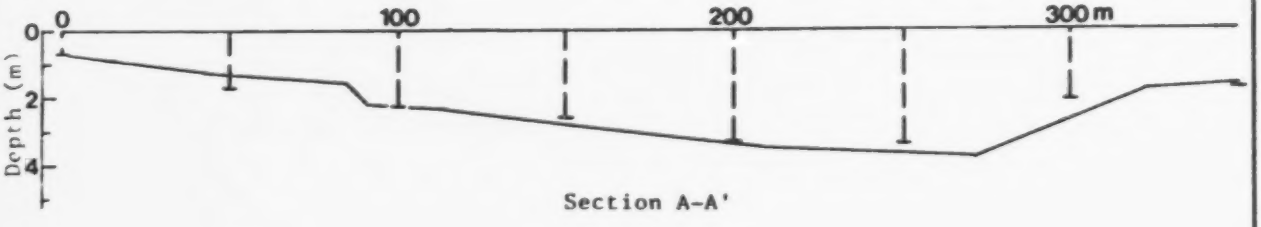
In order to determine whether the impulse radar measurements were affected by seasonal variations, composite data sets were plotted separately for the first and second field programs (Figures 5.13 and 5.14). The slopes from these two regressions were remarkably close, indicating that there was no difference in the propagation velocity between summer and fall.



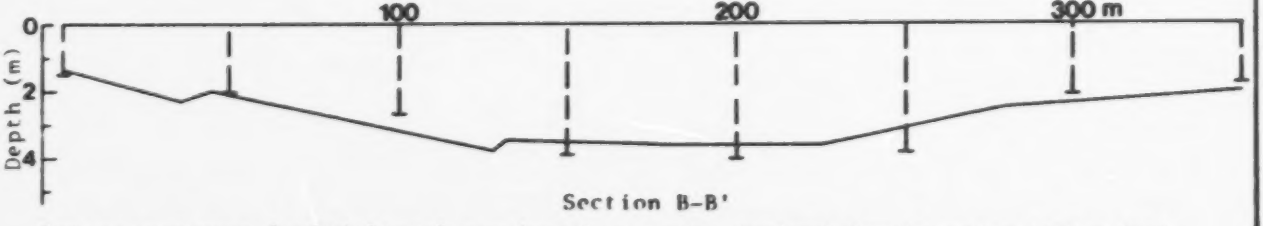
LEGEND

Ditched Area ..... D
Water ..... W
Radar Lines ..... ---
Sample Points .... •

Scale 0 50 100 150 200 m



Section A-A'



Section B-B'

Bottom contours (solid lines) are based on radar derived depths using individual deposit velocities. Broken lines indicate the manual depth measurements at the sample points.

FIGURE 5.10 - FORT MOTEL BOG CROSS-SECTIONS

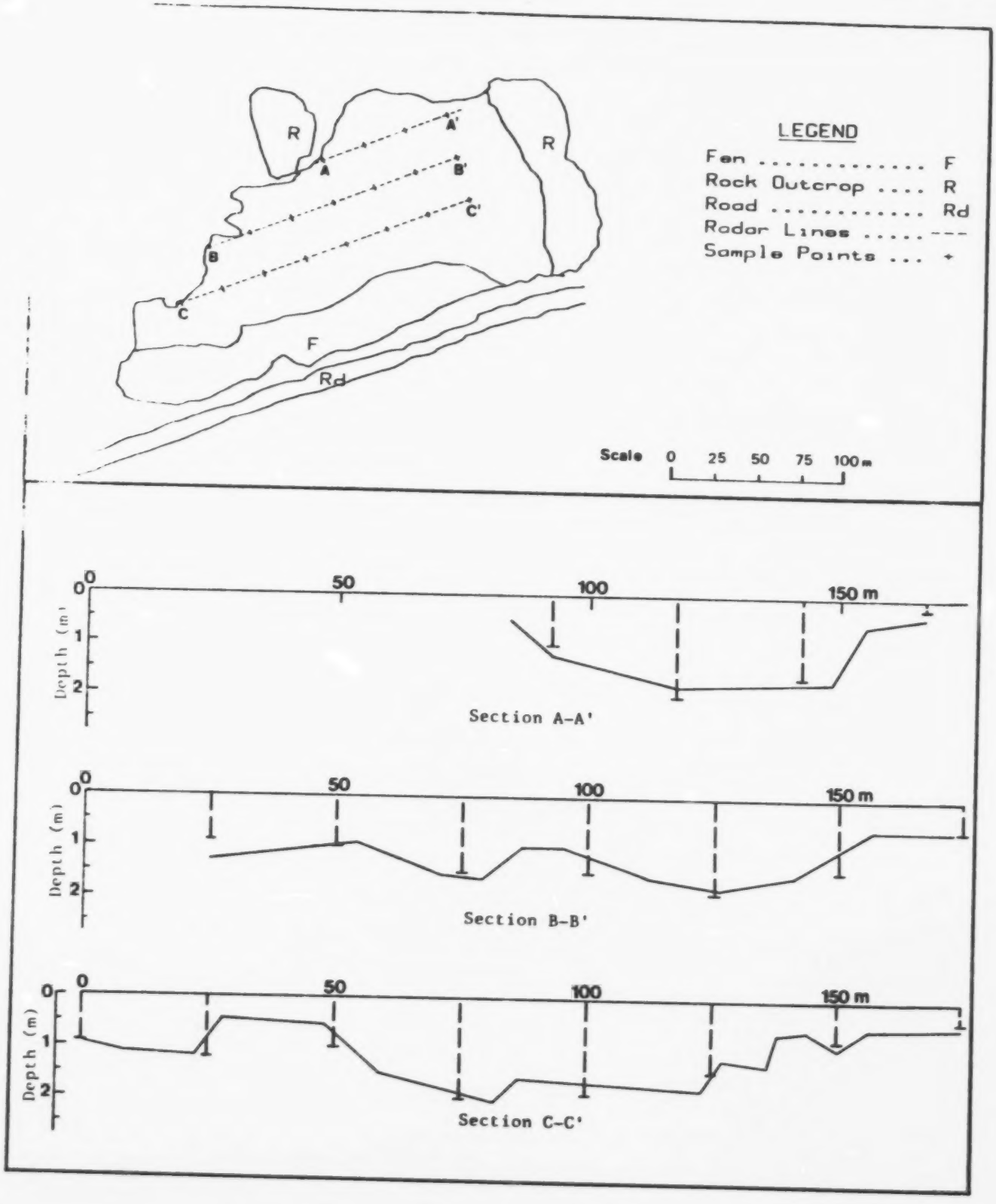


FIGURE 5.11 - WITLESS BAY BOG CROSS-SECTIONS

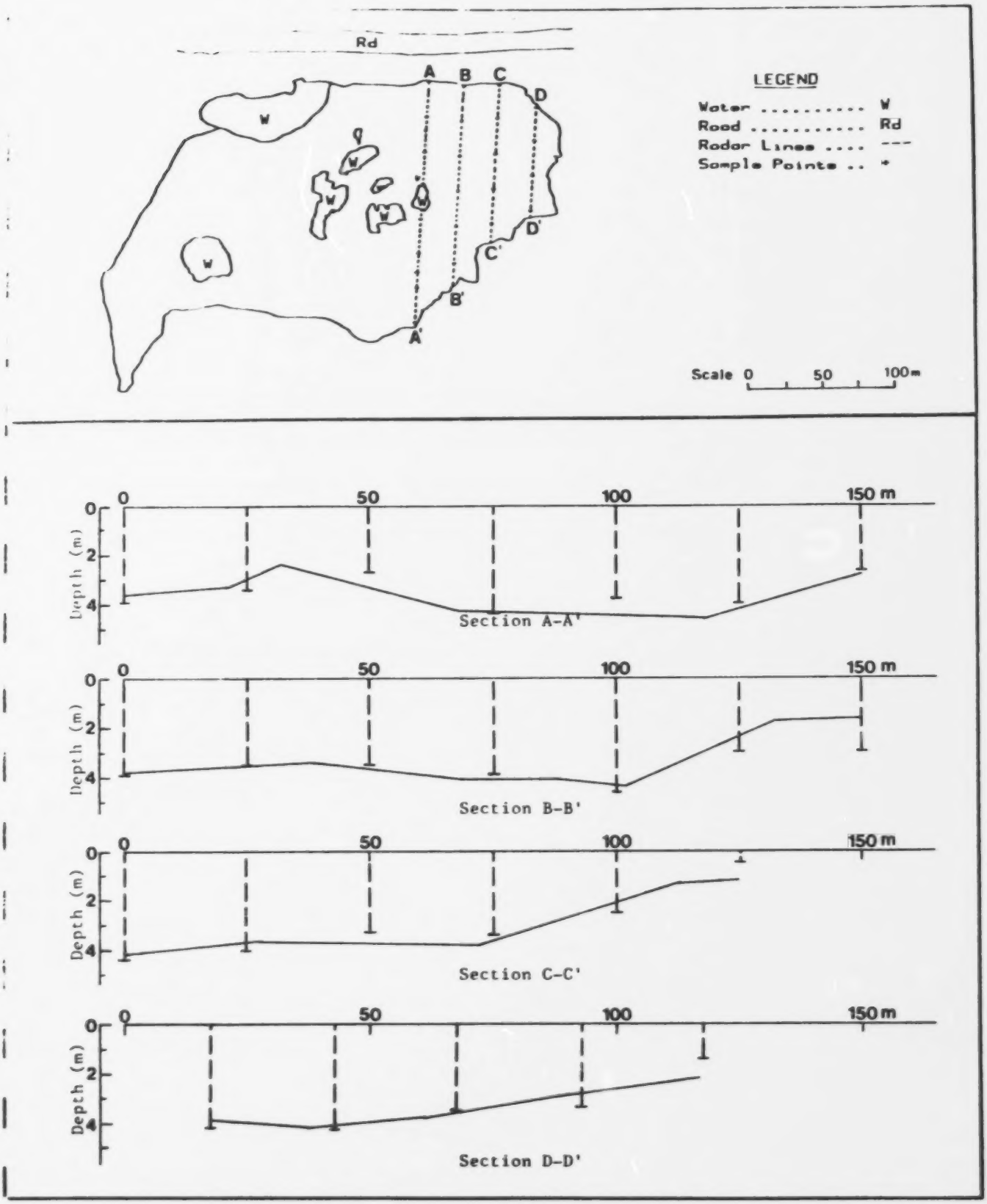


FIGURE 5.12 - WHITBOURNE BOG CROSS-SECTIONS

DEPOSIT: FORT MOTEL BOG			
CROSS-SECTIONAL AREA:			
Line	Calculated based on manual depths	Calculation based on radar profile depths. Individual Bog Velocity	Calculated based on radar profile depths. Composite Velocity
A-A'	833.7 m^2	874.5 m^2	858.1 m^2
B-B'	1010.0 m^2	1053.3 m^2	1033.6 m^2
Calculated Peat Volume (25m line spacing)			
Total	64530 m^3	67473 m^3	66209 m^3

DEPOSIT: WITLESS BAY BOG			
CROSS-SECTIONAL AREA:			
Line	Calculated based on manual depths	Calculated based on radar profile depths. Individual Bog Velocity	Calculated based on radar profile depths. Composite Velocity
A-A'	105.0 m^2	111.5 m^2	104.7 m^2
B-B'	200.0 m^2	184.7 m^2	173.5 m^2
C-C'	209.4 m^2	202.6 m^2	190.3 m^2
Calculated Peat Volume (25m line spacing)			
Total	8930 m^3	8544 m^2	8025 m^3

DEPOSIT: WHITBOURNE BOG			
CROSS-SECTIONAL AREA:			
Line	Calculated based on manual depths	Calculation based on radar profile depths. Individual Bog Velocity	Calculated based on radar profile depths. Composite Velocity
A-A'	538.8 m^2	563.1 m^2	569.4 m^2
B-B'	511.0 m^2	513.1 m^2	518.9 m^2
C-C'	390.6 m^2	394.3 m^2	398.7 m^2
D-D'	350.0 m^2	340.8 m^2	344.6 m^2
Calculated Peat Volume (25m line spacing)			
Total	33650 m^3	33984 m^3	34365 m^3

TABLE 5.3 - CROSS-SECTIONAL AREAS AND CALCULATED PEAT VOLUMES

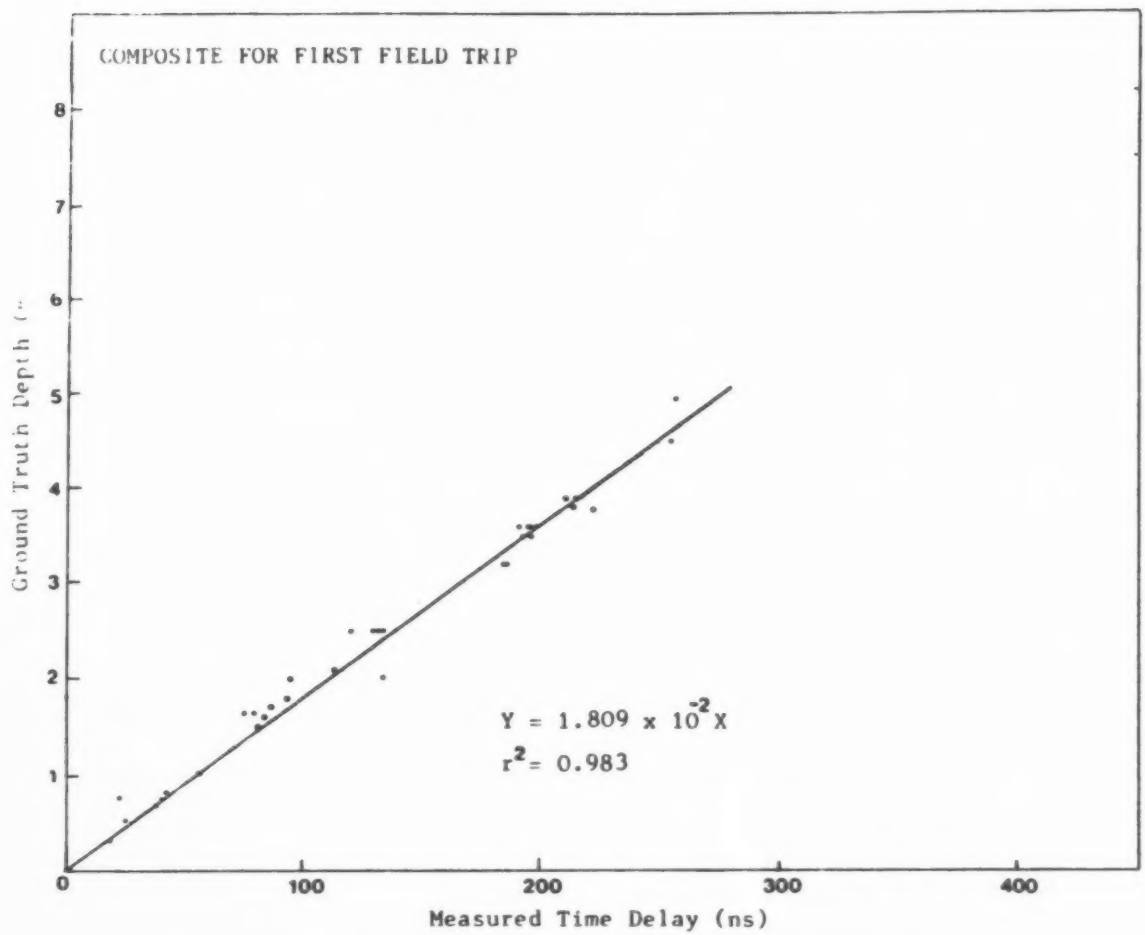


FIGURE 5.13 - GRAPH OF GROUND TRUTH DEPTH VERSUS MEASURED TIME DELAY

From the slope of the straight line fit to the data, the dielectric constant = 68.7 and the propagation velocity = 0.036 m/ns.

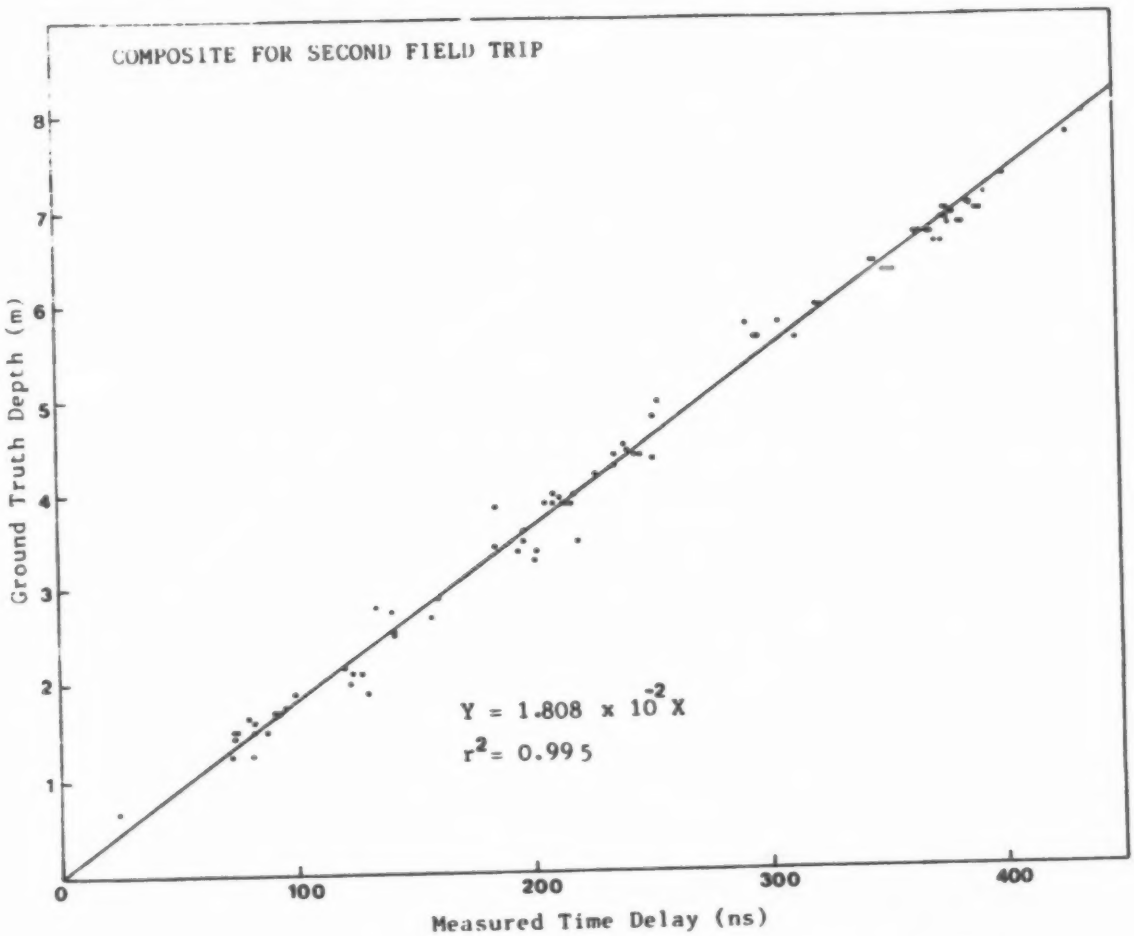


FIGURE 5.14 - GRAPH OF GROUND TRUTH DEPTH VERSUS MEASURED TIME DELAY

From the slope of the straight line fit to the date, the dielectric constant = 68.9 and propagation velocity = 0.036 m/ns

A point-by-point comparison of depths measured on the radar profiles showed average differences of about 8 centimeters between the two programs. Given that the lines actually profiled may have been offset slightly from each other, or that the event marker may have been triggered slightly ahead of or behind the sample stake, the differences in depth were not significant. Qualitatively, the profile records taken over the same transect lines during the two programs were virtually identical. The shape of the bottom contour, the appearance of internal 'layering', and the location of stumps or boulders remained consistent. There were some differences in the horizontal scale because the speed of the ATV was not always the same, but the scales could easily be computed by using the event marks on the records.

During the winter field program, only 120 MHz airborne radar data was collected. Because of the snow cover and the frozen surface layer, it was not practical to remeasure the peat manually at each sample point. At a number of the points, the stakes previously inserted could not be located because of snow drifts or removal. New stakes were laid out for these points, but may not have corresponded exactly to the original positions. For this reason, no attempt was made to quantitatively compare the 'ground truth' depths with the radar wave travel times. In general, however, the range of depths calculated for the transect lines corresponded closely to those measured in the earlier programs, using the same propagation velocity. The profile records were similar in appearence, except for more pronounced systematic noise in the winter data (not caused by environmental factors).

The frozen peat layer, observed to be between 10 and 15 centimeters deep, could not be resolved on the radar record. This was contrary to expectations, since frozen peat should have a much lower dielectric constant than thawed peat, even though most of the moisture is not in a 'free' state. (The dielectric constant of fresh water is 81, whereas the dielectric constant of freshwater ice is 3.2.) Presumably, a thicker frozen layer would be detected and its presence should be corrected for in order to avoid underestimation of the total peat depth.

A thick frozen layer should allow better radar penetration from an airborne platform, since the dielectric change at the air/peat interface would be less pronounced.

CHAPTER 6

EVALUATION OF TECHNIQUE

6.1 INVENTORY PROGRAMS

Peatland inventory programs in Canada have been recently undertaken by a number of provincial governments, and each province has adopted its own approach based on its perceived needs and circumstances. In order to assess the role which impulse radar techniques might play in ongoing or future peat inventory programs, the methodologies used by three provinces (New Brunswick, Newfoundland, and Ontario) are briefly described. These descriptions focus on the data collection aspects of each inventory, since it is in this area that impulse radar techniques could be expected to contribute.

New Brunswick has slightly over 100,000 hectares (ha) of peatlands, of which 85,000 ha had been evaluated by the end of 1980. The first phase of the provincial inventory consisted of a study of available aerial photography, which was then followed by a detailed field assessment of all deposits in excess of 25 ha. A grid sampling system was used on the larger peatlands, while smaller deposits were studied using traverse points. Heavily treed or ponded areas were avoided where possible. Grid lines were cut and chained with sample points established at 100 meter intervals along each line. A core was taken at each point using Hillier sampling equipment and each change in characteristics with depth was recorded as a separate interval. For each interval the peat was classified botanically by the percentage of each species present (to the nearest 10 percent) and by the degree of humification according to the Von Post scale. Wetness, fine fibres, and woody remants were also recorded for each interval. The number of snags (stumps or woody remains)

in the upper 2 metres of the peat was determined by probing around each sample point 10 times in a standard pattern. Additional information recorded at each site included the type of surface vegetation, bottom sediments, and elevation. A total of 21,000 sites were included in this study. (Gemmel and Keys, 1979; Keys, Gemmel, and Ferguson, 1981; and Keys, personal communication).

There are approximately 2,000,000 ha of peatlands on the island of Newfoundland, which comprise 17 percent of the total land area. A provincial peatland inventory was begun in 1978 and is expected to be completed early in 1983. The island was divided into five regions for inventory in successive years; the methodology described is based on the 1980 inventory of Eastern Newfoundland, but essentially the same procedures were followed for the other regions. All peatlands greater than 1 ha in area were mapped and classified from aerial photography. The study area was subdivided into biophysical eco-districts, and the field sampling intensity was based on the area of deposits within each district. Out of a total of 17,525 deposits, 227 were actually visited in the field. A variable grid system, based on the size of each deposit, was used to locate sample points; 2,074 depth measurements were made for volume calculations, while 711 samples were collected and classified by depth, C.S.S.C. (soil) group, Von Post scale, and Munsell color notation. Detailed volume estimates for each type of peat (based on degree of humification) were made by constructing profiles and calculating the proportion of each type. Separate estimates were also prepared using the mean depth of each layer, and these were within $\pm$ 6 percent of the detailed estimates. Results obtained from the sampled deposits were then extrapolated to the other deposits within each district. (Northland Associates, 1981).

Ontario has an estimated peatland area of approximately 26,000,000 ha, of which 9,900,000 ha lies south of the southern limit of permafrost. However, only about 62,000 ha had actually been surveyed by 1980. In order to gain an appreciation of the extent and quantity of peat

resources in the province, the Ontario government commissioned a study to summarize the data which was currently available. The main sources of information were literature, topographic maps (1:250,000), and engineering geology maps (1:100,000). In addition, some spot checks were made on aerial photographs and 1:50,000 topographic maps, while contacts were made with peat researchers in the province. Areas marked as open or forested wetlands on the topographic maps and areas classified as organic terrain on the geology maps were transferred onto 1:500,000 peatlands base maps. Because of the scale factors, only deposits greater than 100 ha were usually included. The province was divided into four regions and the approximate surface area of peatlands was measured from the 1:500,000 maps. The entire Hudson Bay lowland area was considered as a region of continuous peatland. From references in the available literature, the average depth of peat in each region was determined and was used to estimate volumes. The shortcomings of this method are obvious, and the figures from the study had to be considered as first approximations only (Monenco, 1981).

The three programs represent different levels of investigation. Table 6.1 shows a four-level system for classifying peatland inventories, taken from the Ontario study report. Using this system, the New Brunswick program would fall into Level 3 or Level 4; the Newfoundland inventory into Level 2; and the Ontario study into Level 1. The major factors controlling the level of investigation appear to be the areal extent of the peatlands and their accessibility. While the New Brunswick inventory provided the most complete and most detailed information, the cost of acquiring comparable data for a province the size of Ontario would clearly be prohibitive. As suggested in Table 6.1, Level 3 or Level 4 surveys may be confined to regions or specific deposits which are suitable for development. In the following section, the potential of integrating impulse radar techniques into peat inventory programs will be discussed.

LEVEL 1:	PRELIMINARY PEATLAND SURVEY USING MAPS, INFORMATION FROM LITERATURE, AND AIRPHOTO SPOTCHECKS The purpose of the Level 1 survey is to establish a preliminary list of all probable peatlands by using existing maps and checking a number of locations on aerial photographs. The information obtained from maps is supplemented by that from literature. Resource calculations are preliminary and based on interpolation of values gleaned from the literature.
LEVEL 2:	PEAT AND PEATLAND SURVEY BY AIRPHOTOS AND OTHER REMOTE SENSING TECHNIQUES The purpose of a Level 2 survey is to compile a list of all the peat deposits of the Province by using aerial photographs as the main source of information. Each deposit is located, numbered and plotted on a large scale map. The surface area of the open and treed portions is measured, and the extent of ponding is estimated to provide useful information regarding the suitability for development. The range of peat thickness and the distribution of peat types is determined by visiting a limited number of representative deposits in various parts of the Province. Based on the results of this ground truthing, and on knowledge of peatland airform patterns, the thickness of peat and distribution of peat types for the rest of the deposits is inferred. A Level 2 investigation gives a relatively accurate picture of the peat resources for the Province. The results of a Level 2 investigation should be regarded as a basis for the selection of areas with potentially usable peatland resources, warranting a further detailed survey for final selection of a source of peat for a specific project(s). A Level 2 investigation for the Province can be performed in 1-2 years depending on the degree of detail and accuracy needed.
LEVEL 3:	DETAILED GROUND SURVEYS Level 3 surveys can be done either before, concurrently with, or after Level 1 and 2 work depending on how urgently the information is needed. Usually this step follows a Level 2 survey and concentrates on regions found suitable for further investigations, or for establishment of a project. The purpose of this step is to select a number of deposits for final development. This work involves extensive study including sampling of deposits at a suitable density along a grid. The time required varies depending on the size, access and depth of the deposit. Generally, deposits smaller than 100 ha in size can be covered at a rate of 20 ha/day and larger ones, depending on the homogeneity of the deposits, up to 60 ha/day. A Level 3 survey gives detailed information on the size of the deposits, distribution, quantities and qualities of peat types, the basic chemical and physical characteristics of peat in the investigated deposits, the drainability, access, land ownership and other information affecting the suitability of the deposits for development.
LEVEL 4:	SITE-SPECIFIC, PROJECT-ORIENTED ASSESSMENTS The final step in developing a peat deposit for an industrial use is to make a detailed sampling assessment of the peat thickness, distribution of peat types and conduct a surface elevation survey. This work can be carried out on a 100 m grid to enable the establishment of a properly located drainage plan, and the most efficient mining plan. This type of work is done for deposits to be taken into use immediately and is expanded to cover other deposits in the region as the need arises. In connection with this work, a large number (e.g. 1 core/10 ha) of samples for chemical and physical analyses are taken to facilitate planning of the mining sequence.

TABLE 6.1 - LEVELS OF INVESTIGATION FOR PEAT RESOURCE ASSESSMENT (MONENCO, 1981)

6.2 IMPULSE RADAR POTENTIAL

The results of this study, presented in Chapter 5, indicate that impulse radar is a viable technique for the remote determination of peat depth. Impulse radar measurements appear to be as accurate and consistent as those obtained by manual probing of the material, and provide comparable estimates of peat volume. Depending upon the level of absolute or relative accuracy required, a composite propagation velocity may be used to predict the peat thickness or a site-specific velocity may be determined for individual deposits. When used in a profiling mode, impulse radar can accurately portray the shape of the deposit bottom; however, airborne profiles could only be acquired from low altitudes, and were strongly affected by systematic and random noise. At the present time, it does not appear to be possible to infer any physical or chemical properties of peat from the radar return.

Impulse radar techniques can be applied to different aspects of peat resource assessment. The level at which these techniques are eventually implemented will depend upon their acceptance by the potential user communities. It will be necessary to demonstrate that the benefits which can be gained will justify the costs associated with data acquisition and analysis. During the field programs described in this report, ground-based profiling provided the most satisfactory results in terms of detail and ease of interpretaion. This might suggest that Level 3 and Level 4 surveys would be most suited to the use of impulse radar techniques. Such is not necessarily the case, however. In the New Brunswick inventory, for example, peat samples were collected for analysis (along with manual depth measurements) using an intensive grid sampling pattern. Since impulse radar data does not appear to provide any direct information about peat characteristics, it cannot eliminate the need for manual sample collection. It may also be necessary to calculate the radar propagation velocity for each deposit. Even if it can be shown that volume estimates based upon radar profiles are more reliable than those based on manual point soundings, the improvement in reliability is likely to be small (depending on the sampling intensity) and may not warrant the additional effort and expense.

On the other hand, the majority of Canada's peatlands still have not been inventoried even at the Level 2 stage of assessment. This level of investigation is primarily concerned with the quantity of peat which is present in a region rather than with the quality of the material within specific deposits. A Level 2 survey involves mapping peatland areas from aerial photography and collecting field data from a number of representative deposits. Where large areas of peatlands are inaccessible by surface transportation, field costs can be quite expensive and data collection is limited to a relatively short season. In the Newfoundland example cited, the majority of the field work was concerned with obtaining depth measurements, rather than collecting samples for analysis. An airborne impulse radar system could acquire such depth information in a fraction of the time and with considerably less effort than manual methods. Even though the initial success of airborne profiling was somewhat limited (and it should be possible to improve this with a certain amount of research and development), point soundings made with the helicopter on the surface may be sufficient. Precise track recovery should not be critical in this type of survey, and the location of control points could be approximated on existing aerial photography. The savings realized in field time and associated expenses could conceivably recover the cost of the impulse radar system within one or two seasons.

It should not be concluded that impulse radar techniques are of no value in Level 3 or 4 surveys. They may be used to select deposits for more intensive investigation and aid in directing detailed manual sampling. For deposits where less intensive sample collection is planned, additional ground-based profiles could assist in the development of the drainage and excavation strategies as well as indicate the presence of stumps and boulders. But it would appear that in Level 2 surveys the need for information is greater, and the cost/benefit returns could be more quickly realized. Once the utility of impulse radar has been demonstrated for regional reconaissance surveys, it should be easier to gain acceptance in more local or site-specific investigations.

6.3 COST CONSIDERATIONS

There are two elements of cost to be considered if impulse radar techniques are to be used in a peat inventory program: capital expenditures and operating expenses. The ideal radar system would consist of a control unit and an antenna customized for airborne operation; available features should include calibrated gain settings, selectable time windows, a voice recorder, a radar altimeter and an automatic noise removal capability. Such a system might cost between $50,000 and $60,000. Necessary ancillary equipment would include a mounting frame to connect the antenna to a helicopter; a four-channel instumentation tape recorder; a graphic recorder or grey-scale plotter; and possibly a 35 mm or 70 mm camera and mount. This equipment would cost in the vicinity of $15,000 to $20,000, although some savings could be realized if certain items were rented for the duration of each field season and charged off to operating expenses.

The major expenses associated with the operation of an impulse radar in Level 2 surveys would be helicopter costs and labour. Depending upon the amount of ground work which has to be carried out at each site, most of the helicopter time could be used for data collection, rather than waiting for the survey crews to take manual measurements. Given the high costs of helicopter rental ($400 to $500 per hour), this would increase the value returned for each dollar normally spent on transporting crews from one site to another. If necessary, the radar data could be collected by a single operator, although a second person would be very helpful for recording the location of flight lines on aerial photographs, keeping written records, triggering the event marker, and operating the camera. Both individuals would certainly be needed if any ground work was also to be carried out. Once the data was collected, one or more persons would be used to produce profile records from the magnetic tapes, annotate the profiles, and to measure and calculate the peat depths. This does not have to be done in the field, nor is it essential that this work be carried out by one of the field party if

proper documentation is supplied. It should be possible to develop a system which provides peat depths in real time given the propogation velocity, or computer programs could be developed to allow digital processing. The other operating expenses specific to impulse radar data collection are the costs of magnetic recording tapes and plotter paper.

If impulse radar techniques are to contribute significantly to peat inventory programs, they must be economically competitive with conventional manual methods. This means that the capital expenditures must be recovered in terms of savings over a reasonable period of time, while operating expenses during the same period should not exceed those incurred if impulse radar data were not used. It is extremely difficult, however, to make a meaningful cost comparison of radar and manual measurement techniques, since the value of the impulse radar data will depend entirely upon the inventory approach adopted. The most obvious savings from impulse radar would occur when a large number of depth measurements need to be taken. For example, if manual soundings were made every 100 metres along a profile line, it might require up to an hour to cover 1 kilometre (depending on the depth of the peat). An airborne radar profile could be flown over the same distance in approximately 5 minutes; if point measurements were made with the airborne radar, then the time required would be slightly longer, possibly 10 or 15 minutes.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 CONCLUSIONS

Based on the operational experience gained during the field programs and the results of the data analyses, tentative answers can be given to the questions posed as the study objectives:

1) Q: Does impulse radar provide consistent and reliable measurements of peat thickness?

A: For 80 MHz ground-based data, the radar delay times were very consistent with the manually measured 'ground truth' depths within each deposit. Peat thicknesses of up to 8.1 metres were clearly visible. The confidence intervals associated with any given radar-predicted depth value were comparable with the estimated variability of single point manual measurements. It appears that the radar propagation velocity may be significantly different between some deposits, but a standard (composite) velocity can be used in most cases.

2) Q: Can impulse radar provide any additional information on the peat composition or deposit structure?

A: No correlation was found between the radar response and any of the parameters analyzed (parent material, humification, density, moisture content, and conductivity). The ground-based profiles did indicate quite distinct layering within the deposits, but the physical significance of these internal interfaces has yet to be determined. The presence of obstacles (presumed to be boulders or woody remains) was also detected. By providing continuous rather than point data, the profile records provided a very detailed portrayal of the deposit bottom.

3) Q: What are the effects of system frequency?

A: Ground-based data acquired with the 80 MHz antenna yielded the clearest and most detailed results. Attenuation was extremely high for the 400 MHz data, rendering it virtually useless, although some bottom reflections were recieved at depths of up to 2.0 metres. Only minimal differences were observed between the airborne data collected at 80 MHz and 120 MHz.

4) Q: How is the system performance affected by deployment from an airborne platform?

A: In order for sufficient energy to penetrate the air/peat interface, it was necessary to maintain the radar antenna within approximately 2 metres of the deposit surface. Airborne profiles acquired from an altitude of 1.5 metres were much less distnct than ground-based profiles, and were more strongly affected by systematic and random noise. However, the bottom reflections were sufficiently strong to allow depth measurements up to 4.8 metres, the deepest point overflown. Data recorded with the airborne system when the helicopter was set down on the surface appeared to be comparable with ground-based measurements. Differences were observed in the propagation velocities calculated using airborne data, but were probably due to poor track recovery.

5) Q: What are the effects of deposit types?

A: One fen deposit was included in the study, but no 80 MHz data could be collected for it because the peat was too shallow to be resolved. The 400 MHz profiles were too poor in quality to be analyzed quantitatively. Of the five bog deposits, one (a slope bog) exhibited a sig-ificantly higher propagation velocity than the others; it is not known what factors were responsible for this effect. Although the five

bogs differed according to their surface morphology, they could not be characterized in terms of any dominant peat parameter. The variation in predicted depth values differed between deposits, but this was likely caused by the effects of bottom roughness on the 'ground truth' measurements, rather than differences in deposit type.

6) Q: What effects are associated with seasonal variations?

A: No significant differences were found between data collected during the summer and fall. Only airborne data was collected during the winter field program and this could not be analyzed quantitatively because of a lack of reliable 'ground truth' measurements. A thin layer of peat (10 to 15 centimetres) was frozen at the time of the winter data collection, but could not be resolved on the profile records. It was hypothesized that a thicker frozen layer should be detectable, and might have a noticable effect on the radar propagation velocity.

Impulse radar techniques can contribute to several levels of peat resource assessment. However, since they do not appear to provide any information on the quality of the peat, they would seem to be most suited for reconnaissance level surveys. Peat volume estimates based on radar profile records were in close agreement with those calculated from manual depth measurements. The use of a single propagation velocity for all deposits is acceptable if relative accuracy only is required; however, it may be necessary to determine the velocity within individual deposits in order to minimize absolute errors. For the five bog deposits analyzed, the composite radar velocity at 80 MHz was 0.036 metres per nanosecond, corresponding to a dielectric constant of 68.8. The attenuation of the radar signal in peat at 80 MHz was estimated as 8.72 decibels per metre from one experiment.

7.2 RECOMMENDATIONS

The utility of impulse radar for measuring peat thickness has been established, and the technique can now be applied as an operational tool. However, there are a number of areas in which further investigation is warranted, in order to extend the range of useful information which can be derived.

Firstly, it would be desirable to test the technique over a greater number of deposits, in order to study more fully the range of radar propagation velocities. This would allow a study of regional differences (where peat has formed under different climatological conditions) and provide a larger data base for statistical comparison of various deposit types (especially deeper fens). It would also serve to define the limitations of the technique, since maximum penetration depths could not be determined for either ground-based or airborne profiling during the present study. Testing of peatlands in permafrost areas would be valuable, since a large proportion of Canada's peat resources lie within these regions.

The major limitation of impulse radar in inventory programs seems to be the fact that it can only measure the quantity of peat present, rather than the quality (degree of humification or botanical constituents) of the material. Although the preliminary analysis was not immediately encouraging, it may yet be possible to relate the layering observed on the profile records to some change in physical or chemical properties. Additional research into this phenomenon could prove to be extremely valuable if it becomes feasible to eliminate or significantly reduce the need for manual sample collection.

The reflection strengths of different bottom materials was not investigated during this study, since the nature of the substratum was not always apparent from the surrounding terrain, and the Hillier sampler could only be pushed easily through the relatively soft peat. It is

known, however, that the strength of a return is dependent upon the difference in dielectric properties on either side of an interface and it may be possible to characterize the underlying media by calculating reflection coefficients. This would require some additional processing to eliminate noise and gain effects (as was done for the attenuation experiment) and would require a knowledge of the dielectric constants for typical bottom materials. This type of information would be useful for engineering applications (e.g. road or pipeline construction) as well as for inventory purposes.

Finally, research should be directed towards improving the quality of airborne peat profiling, with the eventual objective of developing a radar system specifically for this application. If the level of information provided by ground-based measurements could be combined with the speed and mobility of a helicopter platform, it seems certain that all levels of peat inventories would benefit substantially. Such research would require an evaluation of the optimal centre frequency, impulse waveform, power requirements, and receiver gain characteristics. Automatic noise removal should also be investigated as well as different signal enhancement techniques. Hopefully, the operating altitude for airborne profiling can be increased, which would allow data collection over treed deposits. The development of this type of system would contribute not only to peat inventory programs, but also to a wide variety of other geotechnical investigations.

CHAPITRE 7

CONCLUSIONS ET RECOMMANDATIONS

7.1 CONCLUSIONS

La présente étude a permis de démontrer la possibilité d'obtenir des mesures uniformes et fiables de la profondeur des dépôts de tourbe à l'aide du radar à impulsions. Les données de profil révèlent la présence d'une structure interne de couches dans la tourbe, mais il a été impossible d'établir une corrélation entre les interfaces observées et des variations chimiques ou physiques précises. Les mesures de profils au sol effectuées au moyen d'une antenne de 80 MHz ont donné les meilleures réflexions de fond dans des dépôts dont la profondeur pouvait atteindre jusqu'à 8.1 mètres. A cette fréquence, la résolution était suffisante pour permettre de mesurer de petites variations d'épaisseur et de détecter la présence de débris ligneux et de roches. Les résultats obtenus au moyen d'un système de 400 MHz étaient très mauvais. Les réflexions de fond étaient faibles et irrégulières et ne pouvaient être détectées à des profondeurs supérieures à 2.0 mètres. Puisqu'il était nécessaire pour capter ces signaux d'exploiter le système en gain élevé, les signaux de retour à 400 Hz étaient dominés par des bandes de bruit systématique et des crêtes de bruit aléatoire.

Les données en vol ont été obtenues au moyen d'antennes de 80 et de 120 MHz. Seules des différences minimes ont pu être observées entre les deux fréquences, bien que la quantité de données à 80 MHz était limitée en raison du support d'antenne inadéquat. Bien que moins clairs que les mesures au sol, les profils en vol suffisaient pour des profondeurs allant jusqu'à 4.8 mètres, le plus profond des points survolés. Les mesures de profondeur obtenues lorsque le système embarqué était directement en contact avec la surface du dépôt ont montré une forte augmentation de l'intensité du signal réfléchi, comparable à celle des mesures au sol. L'intensité du signal réfléchi décroît rapidement avec l'altitude, ce qui limite l'altitude des mesures en vol à environ 2 mètres.

La valeur moyenne de la constante diélectrique de la tourbe (à 80 MHz), calculée par la combinaison de toutes les profondeurs de référence au sol et des durées de retard correspondantes, était de 71.0, ce qui correspond à une vitesse de propagation radar de 0.036 mètre par nanoseconde.

La comparaison des valeurs obtenues sur différents dépôts et au cours des deux programmes d'études sur le terrain a mis en évidence de faibles différences des propriétés diélectriques. Toutefois, il est impossible de tirer des conclusions définitives en ce qui a trait aux variations saisonnières ou géographiques, en raison du manque de précision absolue des mesures manuelles et de l'effet d'uniformisation de l'enveloppe radar. Même si les différences apparentes de la vitesse de propagation ne résultaient pas d'erreurs de mesure, l'effet net sur les mesures de profondeur effectuées au radar ne serait pas important aux fins des relevés. Les évaluations du volume de la tourbière établies à partir des données manuelles s'accordaient à 5% près avec celles obtenues par procédé radar.

L'expérience pratique acquise pendent la collecte des données sur le terrain a montré la rapidité et l'efficacité de la détermination du profil au moyen du radar à impulsions par rapport aux mesures manuelles de la profondeur. On a rencontré certaines difficultés relatives à la précision du rétablissement de la poursuite des données en vol, mais cela ne devrait poser aucun problème majeur au cours des relevés de reconnaissance. Le rôle du radar à impulsions dans les futurs programmes de relevés dépend entièrement des besoins définis par l'usager; toutefois, leur valeur pour l'échantillonnage d'importants dépôts de tourbe inaccessibles semble indiscutable.

7.2 RECOMMANDATIONS

Comme nous l'avons dit, l'utilité du radar à impulsions pour la mesure de la profondeur de la tourbe a été démontrée et la technique peut maintenant être appliquée à une siutation réelle. Toutefois, il existe un certain nombre d'aspects qui nécessiteraient des recherches supplémentaires afin d'augmenter la gamme des informations que l'on peut tirer de ces mesures.

En premier lieu, il serait souhaitable de soumettre la technique à des essais sur un plus grand nombre de dépôts, particulièrement dans d'autres régions. Cela permettrait d'étudier les différences régionales (la tourbe s'étant formée dans des conditions climatiques différentes) et produirait une base de données suffisamment étendue pour effectuer une comparaison statistique de différents types de dépôts (particulièrement dans les marais plus profonds). Cet essai permettrait aussi de définir les limites de la technique puisque les profondeurs maximales de pénétration n'ont pu être déterminées au cours de la présente étude, ni dans le

cas des mesures au sol, ni dans le cas des mesures en vol. Des essais dans des régions de sols tourbeux ou de pergélisol seraient fort utiles puisqu'une grande partie des ressources canadiennes de tourbe se trouvent dans ces régions.

La principale contrainte imposée aux programmes de relevées par radar à impulsions est que ce radar ne mesure que la quantité et non la qualité de la tourbe (degré d'humification et constituants végétaux). Bien que les résultats de l'analyse préliminaire n'aient pas été encourageants on n'écarte pas la possibilité d'établir une relation entre les structures de couches observées sur les relevés de profil et les propriétés physiques ou chimiques de la tourbe. Des recherches supplémentaires dans ce domaine pourraient s'avérer extrêmement utiles s'il était possible d'éliminer ou de réduire de façon substantielle la collecte d'échantillons.

L'intensité de réflextion des divers matériaux de fond n'a pas été étudiée au cours de cette étude, puisque la nature du substrat n'était pas toujours apparente d'après le terrain environnant et que l'échantillonneur Hillier ne pénétrait facilement que dans la tourbe relativement molle. On sait toutefois que l'intensité du signal de retour dépend de la différence entre les propriétés diélectriques de part et d'autre d'une interface et il pourrait être possible de classer le médium réflecteur souterrain en se basant sur les coefficients de réflexion. Cela demanderait des traitements additionnels pour éliminer les effets du gain et du bruit (ce qui a été fait dans l'expérience d'atténuation) et exigerait la connaissance des constantes diélectriques des matériaux de fond types. Ce genre d'information serait utile dans les projets de construction de route, de pipelines, etc. et dans l'établissement de relevés.

En dernier lieu, il faudrait mettre au point un système de radar à impulsions adapté aux utilisations pratiques de mesures de la tourbe; ce système est décrit dans le chapitre 6. Le système embarqué C-CORE utilisé au cours de cette étude a été conçu pour mesurer l'épaisseur de la glace et, à cause des altitudes de vol normales pour cette application, les 100 premières nanosecondes du signal de retour étaient fortement brouillées par des oscillations parasites et le bruit du système. Sur les autres plans, ce système présentait la plupart des caractéristiques essentielles d'un prototype d'appareil de mesure du profil de la tourbe. Il faudrait s'efforcer de déterminer s'il est possible d'accroître l'altitude de mesure en vol du profil, puisque cela augmenterait grandement l'utilité du système dans le cas de dépôt situés dans des régions boisées. L'application de ce système radar ne doit pas se limiter uniquement aux mesures sur la tourbe; il pourrait servir à une grande variété d'autres études géotechniques.

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APPENDIX A

CANADIAN WETLAND REGISTRY - CLASSIFICATIONS OF WETLAND FORMS

REMOTEC
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Telex 016-4939

Table 1: Classification key to bog wetland forms

1. Surface raised above the surrounding terrain
   2. Surface convex
      3. Core frozen; abruptly domed; usually in fens
         4. Over 1 m high, diameter up to 100 m ---------- Palsa Bog
         4. Less than 1 m high, diameter up to 3 m ---------- Peat Mound Bog
      3. Core not frozen
         5. Convex surface small (1-3 m dia.) occurring in fens ---------- Mound Bog
         5. Convex surface often extensive; not occurring in fens ---------- Domed Bog
   2. Surface flat to irregular
      6. Core perennially frozen
         7. Surface with network of polygonal fissures
            8. Surface even ---------- Polygonal Peat Plateau Bog
            8. Surface with high centres in a polygonal network ---------- Lowland Polygon Bog
         7. Surface without polygonal fissures
            9. Surface about 1 m above the surrounding fen ---------- Peat Plateau Bog
      6. Core not frozen
         10. Bogs generally tear-drop shaped ---------- Northern Plateau Bog
         10. Bogs not tear-drop shaped; abundance of surface water ---------- Atlantic Plateau Bog

1. Surface not raised above surrounding terrain
   11. Surface relatively level
      12. With abrupt marginal peat walls ---------- Collapse Bog
      12. Without marginal peat walls
         13. Adjacent to water bodies
            14. Floating ---------- Floating Bog
            14. Not floating ---------- Shore Bog
         13. Not adjacent to water bodies
            15. Surface flat; topographically confined
               16. Basin deposit; depth greatest in center ---------- Basin Bog
               16. Flat deposit; depth generally uniform ---------- Flat Bog
            15. Surface flat to undulating, often appreciably sloping
               17. Surface pattern of ridges and pools distinct ---------- String Bog
               17. Surface pattern of pools usually absent; extensive ---------- Blanket Bog
   11. Surface not level
      18. Core not frozen
         19. Surface concave ---------- Bowl Bog
         19. Surface appreciably sloping ---------- Slope Bog
      18. Core perennially frozen
         20. Surface appreciably sloping ---------- Veneer Bog

Table 2: Classification key to fen wetland forms

1. Surface not raised above surrounding terrain except in low hummocks and ridges	
2. Surface pattern of ridges and depressions	
3. Sub-parallel pattern of ridges and furrows	
4. Broad pattern; often very extensive	
5. Northern regions; lowland drainage; peat deep	Northern Ribbed Fen
5. Atlantic regions; mainly upland drainage; peat shallow	Atlantic Ribbed Fen
4. Narrow ladderlike pattern; along bog flanks	Ladder Fen
3. Reticulate pattern of ridges	Net Fen
2. Without pronounced surface pattern	
5. Featureless, adjacent to water bodies	
6. Floating	Floating Fen
6. Not floating; located in main channel or along banks of continuously flowing or semi-permanent streams	Stream Fen
6. Not floating; located along shores of semi-permanent or permanent lakes	Shore Fen
5. With surface water or filled depressions; not adjacent to water bodies	
7. Depressed thaw hollows	Collapse Fen
1. Surface raised or appreciably sloping	
8. Mounds with frozen core in patterned fens	Palsa Fen
8. Without frozen core	
9. Surface irregular due to upwelling water	Spring Fen
9. Surface regular but sloping	Slope Fen
1. Surface flat or depressional	
10. Core perennially frozen	
11. Surface with network of polygonal fissures	Lowland Polygon Fen
10. Core not frozen	
12. Surface level without pronounced surface pattern	Horizontal Fen
12. Occupying abandoned glacial meltwater spillways, intermittent drainage courses or open-ended, eroded channels	Channel Fen

Table 3: Classification key to marsh wetland forms

1. Influenced by marine tidal water	
2. In river estuaries or connecting bays where tidal flats, channels and pools are periodically inundated by water of varying salinity	
3. Located above mean high water levels; inundated only at highest tides and/or storm surges	Estuarine High Marsh
3. Located below mean high water levels; frequently inundated	Estuarine Low Marsh
2. On marine terraces, flats, embayments or lagoons behind barrier beaches, remote from estuaries, where there is periodic inundation by tidal brackish or salt water, including salt spray	
4. Located above mean high tide levels; inundated only at flood tides	Coastal High Marsh
4. Located below mean high water tide levels	Coastal Low Marsh
1. Occupying valleys, gullies, channels, streams, floodplains and deltas	
5. Adjacent to, or flooded by, flowing water	
6. Located on active fluvial floodplains adjacent to channels	Floodplain Marsh
6. Occupying shorelines, bars, streambeds or islands in continuously flowing water courses	Stream Marsh
6. Occupying abandoned glacial meltwater spillways, intermittent drainage courses, or open-ended, eroded channels	Channel Marsh
5. Occupying deltas with open drainage or water circulation due to unrestricted connections to active river channels and/or lakes	
7. Seasonally inundated	Active Delta Marsh
7. Inundated only during infrequent high river flows or wind tides	Inactive Delta Marsh
1. Occupying topographically defined catch basins, fed by local runoff or ground water	
8. Flat or concave basins in topographic low areas at the terminus of internal drainage systems, forming a close catchment for ground water discharge or surface inflow	Terminal Basin Marsh
8. Shallow, gently sloping depressions that occur as natural swales or that occupy intervening areas between ridges or undulations on low-relief landforms	Shallow Basin Marsh
8. Sharply defined catch basin, usually located in high or intermediate topographic positions on moderate to high-relief hummocky moraine, glacio-lacustrine or glacio-fluvial landforms	Kettle Marsh
1. Not in topographically defined catch basins	
9. Occupying groundwater discharge sites, usually on or at the base of slopes	Seepage Track Marsh
9. Occupying the shores of semi-permanent or permanent lakes	Shore Marsh

Table 4: Classification key to swamp wetland forms

1.	Adjacent to water body	
	2. Located along banks of continuously flowing or semi-permanent streams	Stream Swamp
	2. Located along shores of semi-permanent or permanent lakes	Shore Swamp
1.	Not adjacent to permanent water body	
	3. In topographically defined basins	
	4. On perimeter of peatlands	Peat Margin Swamp
	4. Basin deposit; depth greatest in centre	Basin Swamp
	3. Not in topographically defined basins	
	5. Flat deposit; depth generally uniform	Flat Swamp
	5. Poorly drained area; associated with floodplains	Floodplain Swamp
	5. Discharge area; surface irregular	Spring Swamp

Table 5: Classification key to shallow water forms

1.	Inland; fresh to saline water bodies less than 2 m deep	
	2. Continuously flowing water confined to main water course	Stream Water
	2. Intermittently flowing water to discontinuous surface flow, confined to glacio-fluvial eroded spillways	Channel Water
	2. Intermittent flow or overbank flooding; impounded behind levees or ridges on alluvial deposits	
	3. On river floodplains	Oxbow Water
	3. On deltas	Delta Water
	2. Surface water catchment in topographically defined basins	
	4. Basins in topographic low areas at terminus of drainage	Terminal Basin Water
	4. Shallow, gently sloping basins with relatively uniform depth	Shallow Basin Water
	4. Relatively deep, bowl-shaped basins with moderately sloping sides	Kettle Water
	2. Not in topographically defined catch basins	
	5. Occupying the shallow shore zone of semi-permanent or permanent open water bodies	Shore Water
1.	Coastal, estuarine or marine water bodies less than 2 m deep	
	6. Brackish water bodies located above mean high tide zone	Nontidal Water
	6. Estuarine channels or bays periodically inundated by fresh and brackish water	Estuarine Water
	6. Coastal lagoons or bays primarily influenced by tidal action and marine salt water	Tidal Water

APPENDIX B

MANUFACTURERS SPECIFICATIONS FOR IMPULSE RADAR SYSTEMS

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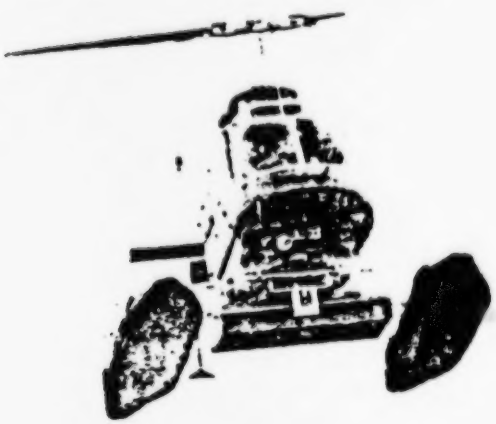
Airborne Impulse Radar



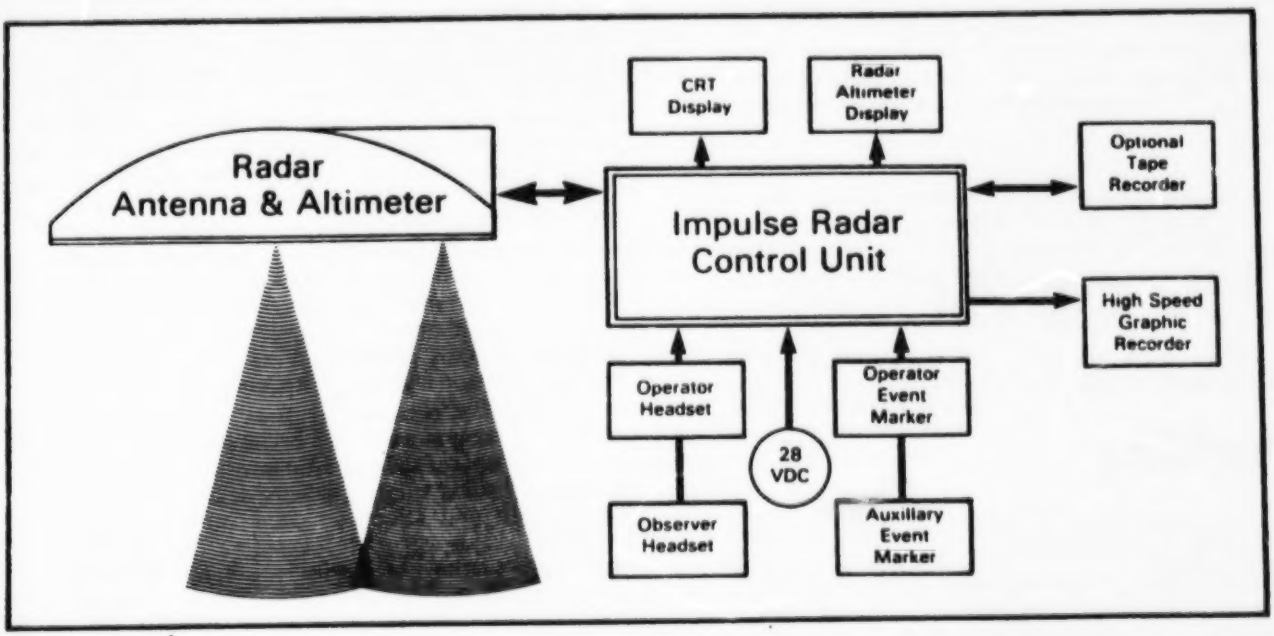
Designed primarily for airborne sea ice thickness profiling, the **INSTRUMAR** Impulse Radar Model 100 can also be used for fresh water ice thickness measurement. The system can be custom configured to suit user requirements for a variety of industrial and scientific applications such as airborne draft measurement of small icebergs or peat bog depth profiling.

The package includes a shielded antenna, M.O.T. approved for "hook" deployment on Bell 206L or B helicopters. Radar control unit, high speed graphic recorder and peripherals are housed within the aircraft. Operator/observer communications are logged on a stereo cassette recorder built into the control unit. A radar altimeter provides operator and pilot with precise height information for controlled low altitude surveys.

- High scan rate (256/sec) provides ice surface coverage of 10 cm/scan at a horizontal velocity of 25 metres/second
- Fixed time window allows precise calibration and reduced operator error
- Time-range measurements in excess of 100 metres of freshwater ice are possible
- Exponential time gain amplification for path loss compensation
- Simplified operator control functions permit easy handling with minimum error
- Shielded antenna reduces systematic noise
- "Four point" antenna mount for ultrastable "hook" installations on Bell 206L and B helicopters
- Microprocessor controlled real time background noise removal

INSTRUMAR Limited

p.o. box 13246, St. John's, Newfoundland, A1B 4A5, (709) 726-8460, telex 016-4794



MODEL 100 SPECIFICATIONS:

Centre Frequency:	120 MHz
Approx. Bandwidth:	80 to 180 MHz
Approx. Pulse Length:	10 ns
Antenna Size:	148 cm x 120 cm x 36 cm
Antenna Deployment:	Transceiver only
Antenna Mount:	"hook" deployed frame for Bell 206B and Bell 206L helicopters
Performance Figure:	≃ 115 dB (includes receiver gain)
Peak Power:	50 Watt
Scan Rate:	256 or 64 scans/second
Range Window:	90 or 360 ns (can be modified to suit application)
Altimeter:*	Display: $3^1/_2$ digit LCD Range: 45′ to 2000′ Accuracy: 45′ to 100′ ± 5% 500′ to 2000′ ± 7%
Surface Pulse/Altitude Offset Control:	Manual Mode – 0′, 50′, 100′, 200′ Auto (altimeter) – 50′ to 275′
Display:	"A" scope CRT (5 x 3.5 cm) and real time paper chart profiling
Dynamic Range:	66 dB for +3 dB S/N
Max. Signal Gain Available after Receiver:	48 dB (excluding time gain)
Max. Time Gain Available after Receiver:	24 dB
Recording:	Synchronous start and stop voice recording on two track cassette Grey level paper chart recorder for in-flight processing Optional analog data logging on 4 channel magnetic tape
Power Requirements:	Control module – 100 watts at 28 VDC ± 2 VDC
Physical Dimensions (mm):	Control module – 585 x 350 x 340 Mini-fax chart recorder – 400 x 254 x 254
Weight:	Control module – 19.00 kg Mini-fax chart recorder – 7.27 kg
Optional Mag Tape Recorder	
Power Requirement:	60 watts at 12 – 30 VDC
Dimensions (mm):	482 x 140 x 432
Weight (kg):	17

*Calibrated in feet compatible with existing North American aircraft systems

Electromagnetic Subsurface Profiling

Electromagnetic Subsurface Profiling (ESP) is an advanced impulse radar procedure that is performed with a SIR SYSTEM. The System transducer is moved along a line while the System Recorder produces a continuous high-resolution profile of the subsurface. The unique feature of the ESP procedure is its ability to automatically generate a continuous map of subsurface features — not a point-by-point sample from which extrapolations are made, but a complete high resolution profile.

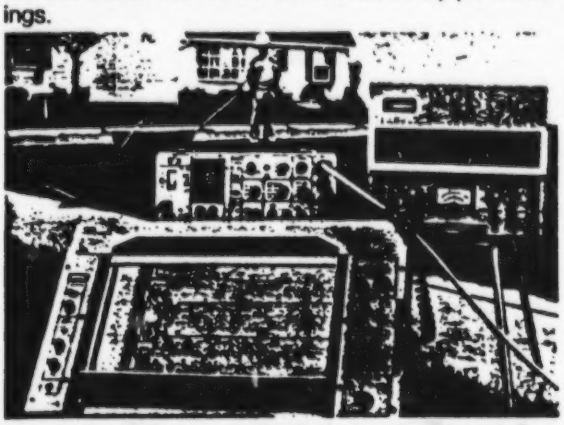
An electromagnetic impulse is propagated into the media from a Transducer unit on its surface. When the impulse strikes an interface between two materials of differing electrical properties — a soil-bedrock interface, a soil-water interface, a pipe buried in soil — some of the impulse energy is reflected and the rest continues on through the material to other interfaces. The reflected signals are received by the Transducer where replica waveforms of the transmitted pulse followed by the reflected signals are generated and sent back to system Control Unit to be monitored on its oscillograph, printed on a graphic recorder, and recorded on magnetic tape. The graphic record of the signal waveforms is a close approximation of the interfaces one would see in a vertical wall of a trench dug along the path of the Transducer.

The ESP procedure has been used successfully to locate buried objects such as pipes; map the bottom topography of fresh water rivers and lakes; measure fresh water ice and sea ice thickness; locate ice wedges in permafrost; and profile bedrock interfaces beneath the soil.

In areas of low soil conductivity, the depth range of the electromagnetic impulse can be as much as 30 meters. High conductivity soil inhibits transmission of the impulse energy, causing the depth of penetration to be limited in some areas. The radar impulses are also blocked by networks of iron or steel, such as those used as reinforcements in concrete highways. However, the higher frequency transducers can penetrate around some reinforcing.

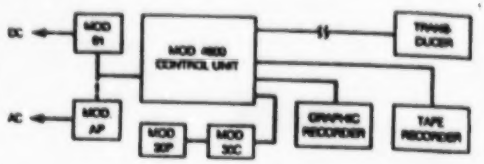
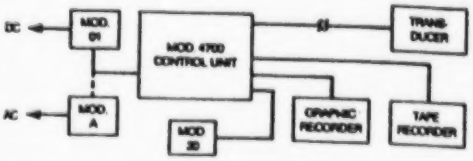
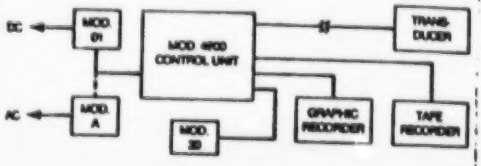
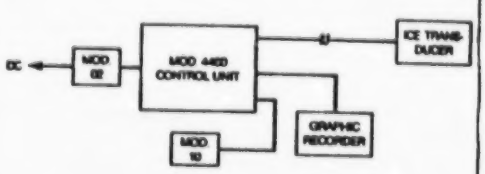
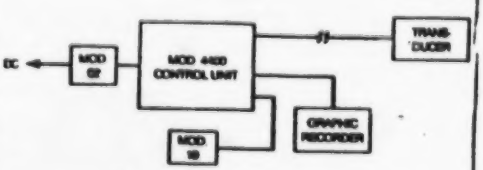
The uses of ESP are many and varied. For anyone who has ever wished he could see through the surface beneath his feet, ESP is the answer:

- For a utilities engineer who must plan new lines or locate existing ones to make repairs or add tie-ins, ESP is a time and money saver. Test pits aren't needed, traffic is only momentarily interrupted for each scan, and interpretation of the ESP printout will give accurate information on both the location and depth of underground systems. Boulders and bedrock interfaces may also be located. Plans can then be made to avoid obstacles and make the most efficient use of time.
- For a contractor planning a major construction project, ESP provides the lay of bedrock, the location of soil interfaces, the size and location of boulders, and possible areas of subsidence. Knowing in advance what is underneath will help prevent costly delays and changes in mid-project.
- For an oil driller, a pipeline engineer, or a research scientist working in the Arctic or Antarctic, ESP is a vital aid. On sea ice, ESP is used to assure the safety of camps, landing strips, and vehicles by measuring ice thickness and detecting hidden cracks and crevasses. Along pipeline routes on permafrost, ESP detects the presence and size of ice wedges beneath the surface so they can be avoided. Glacial ice depth and structure can also be detected, recorded, and studied.
- For an engineer interested in going through or under fresh water lakes and rivers, ESP records the bottom contours. ESP has also been used to look through to the sub-bottom to detect interfaces and pipe crossings.



New uses for ESP are constantly being discovered. Surveys using ESP to locate areas of interest at archaeological sites have had successful results. ESP is being used as a coal seam thickness sensor to facilitate highwall coal mining. In addition, surveys along tunnel walls have been performed to gain information about the structure of the surrounding rock to detect potential mining hazards. Borehole transducers are available to lower into boreholes, profiling laterally greatly extending borehole data.

Computer processing is now being used to remove background noise and thus enhance ESP data. Further computer analysis techniques are being developed to add to the information gained from the data by studying the shape of the reflected waveforms.

✱SIR SYSTEM 8 Scientific with Processor		SIR SYSTEM-8 is the most advanced Subsurface Radar System commercially available. In addition to all the capabilities of the SIR SYSTEM-7, this system contains a built-in microprocessor programmed for real-time or off-line signal enhancement. The Model 30P processor control unit allows easy selection of one of the prestored programs and time constants best suited for the users current applications.
SIR SYSTEM 7 Scientific		SIR SYSTEM-7 provides its user with maximum flexibility in operating control functions. Digital display dials are used to indicate the amount of amplification applied to the input signal and full scale range adjusted by the operator. Other controls adjust range-gain, scans per second, signal position, function and recorder motion. Push button switches allow the operator to superimpose three different marker patterns on the recorded data.
SIR SYSTEM 6 Utility		SIR SYSTEM-6 allows operation by a non technical operator. Controls of the Model 4600 have been simplified and some preset. Operator set up and control error has been reduced to a minimum. This general purpose "utility" system is employed for a variety of applications including pipe locating and mapping, geotechnical and archaeological.
SIR SYSTEM 5 ICE		SIR SYSTEM-5 provides immediate graphic records of sea or fresh water ice bottom profiles. The special dual element Model 3020 transducer compensates for error caused by the anistropic characteristic of sea ice in certain areas. A rugged 15 meter tow/control cable provides a simple reliable method for towing the sled type transducer behind a survey vehicle during the profiling operation. Ice thickness is continuously displayed on the graphic recorder assuring safe travel over sufficiently thick ice.
SIR SYSTEM 4 Direct Print		SIR SYSTEM-4 is used where immediate subsurface profile records are required and the tape recorder capability is not desired for operational or economic reasons. The Model 4400 Control Unit has, like all SIR SYSTEM Control Units, a built-in oscilloscope monitor that displays the wave shape of each individual radar scan being recorded.

ACCESSORIES

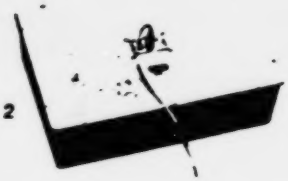
SIR SYSTEMS are shipped with all components, a calibrator, cables, manuals, etc., ready for immediate field operation. You need only supply primary DC or AC power and a survey site.

All transducers manufactured by GSSI plug directly into any SIR SYSTEM and can be ordered for delivery with your system or in the future. GSSI will help determine the best transducer for each of your applications.

A SIR SYSTEM purchase includes a training course at the GSSI facility that teaches system operation, maintenance and data interpretation.

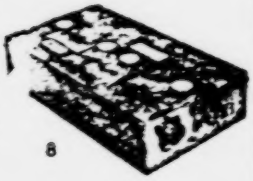
Transducers

1


2

3

#	MODEL NO.	CENTER FREQUENCY	PULSE WIDTH	APPLICATION
1	3112	80MHZ	6ns	Deep probing—mono or bi-static
2	3110	120	5	Light weight version of 3055
3	3055	120	5	General Purpose
4	3020	120	5	Sea ice profiling
5	H6/110	120	5	Borehole T/R or cross hole
6	3105	300	3	High resolution—shielded
7	3103	400	2.5	High resolution bi-static
8	101C	900	1	Very high resolution—shielded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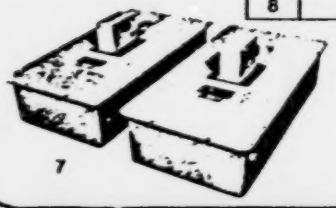
5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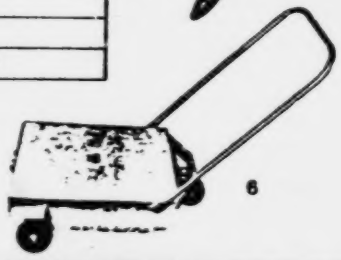
4

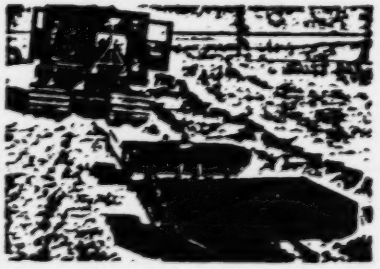

6

the world of GSSI

From the hot sands of Saudi Arabia to both Poles, GSSI equipment has performed with distinction under extreme environmental conditions. Whether the desired target is a cavity in Florida, a massive ice wedge in permafrost at Tuktoyuktuk, a gas pipeline crossing under the Mississippi River, a water main in downtown Tehran or a safe route across sea ice to Melville Island, GSSI Systems are ready. A SIR SYSTEM may be the answer to one of your subsurface problems.

Let Us Help

For further information, please write, call or visit us. We will be happy to assist with your project and provide a firm price and delivery quotation for a standard or custom system best suited to meet your needs.



Geophysical Survey Systems, Inc.

15 FLAGSTONE DRIVE
HUDSON, NEW HAMPSHIRE 03051 U.S.A. (603) 889-4841 TELEX NO. 953038 (GSSIHSUN)

APPENDIX C

RESULTS FROM WIDE ANGLE REFLECTION AND REFRACTION MEASUREMENTS
FOR INDIVIDUAL DEPOSITS

REMOTEC
Remotec Applications Inc.

Remotec Applications Inc.,
Mailing Address: P.O. Box 5547,
St. John's, Newfoundland,
Canada, A1C 5W4

Business Address: K-Mart Plaza,
Topsail Road, Suite 202
Telephone: (709) 364-1779, -2032,
-2033
Telex 016-4939

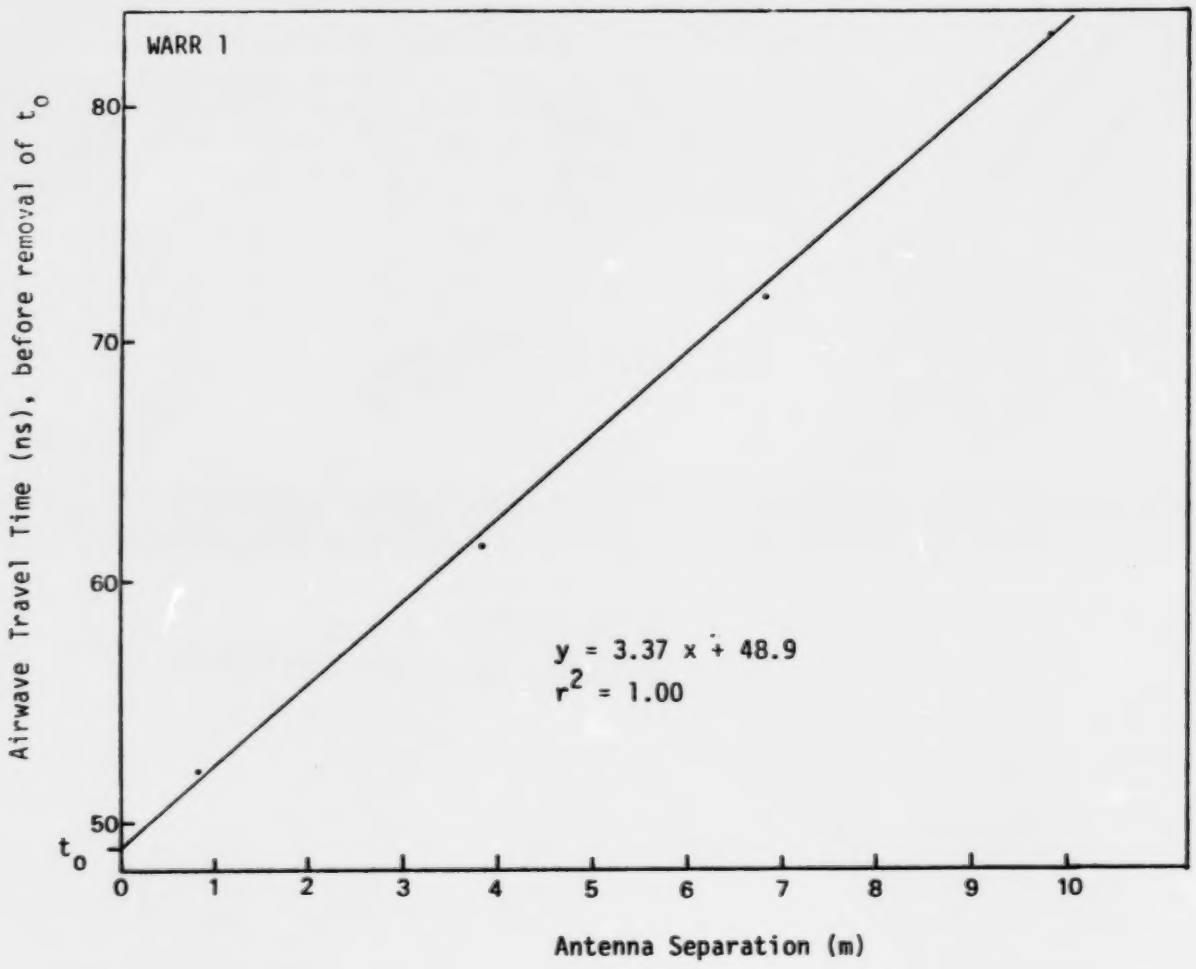


FIGURE C.1 - GRAPH OF AIRWAVE TRAVEL TIME VERSUS ANTENNA SEPARATION - Linear regression yields t_o = 48.9 ns and speed of wave c = 3.0×10^8 m/s.

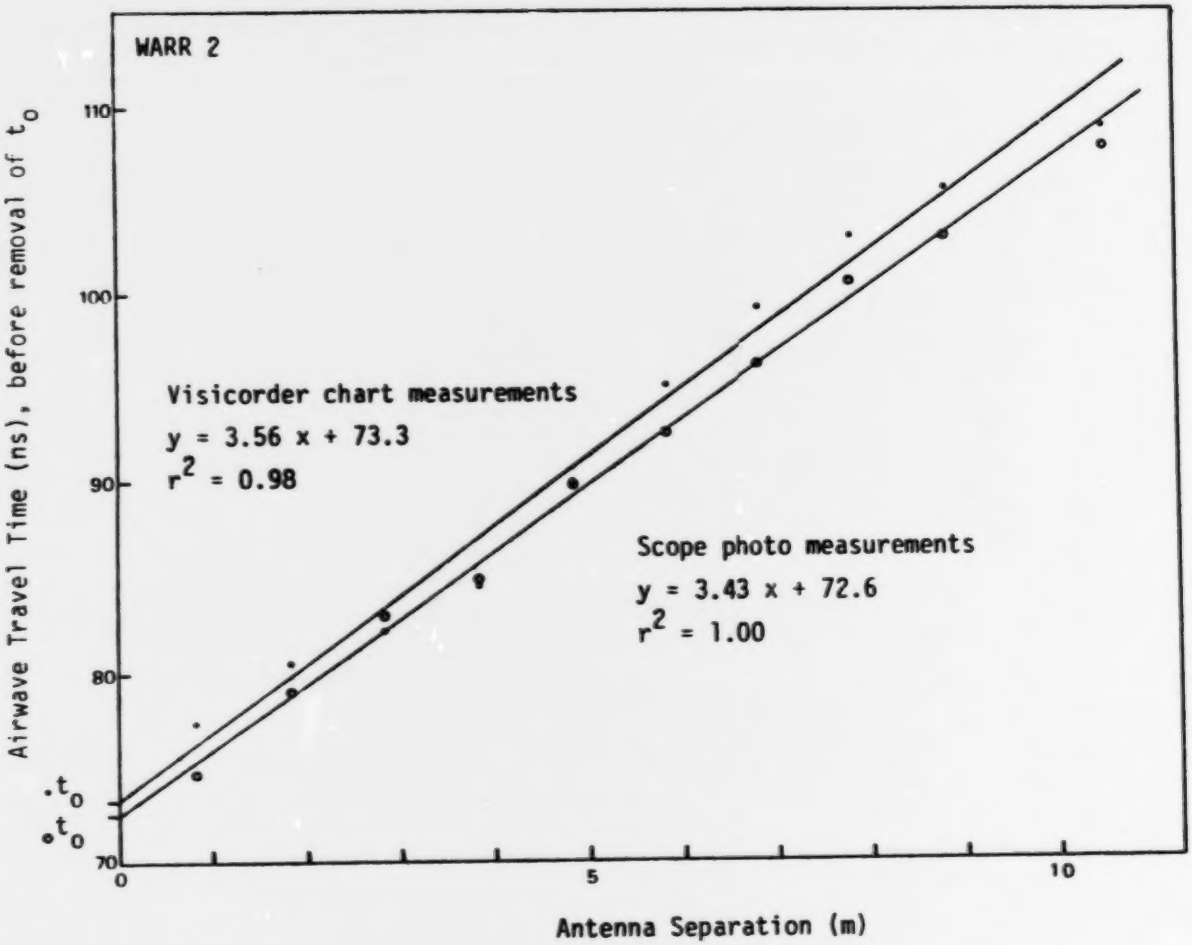


FIGURE C.2 - GRAPH OF AIRWAVE TRAVEL TIME VERSUS ANTENNA SEPARATION - Linear regression yields t_o = 73.3 ns with speed of wave c = 2.8 x 10^8 m/s for visicorder chart measurements, and t_o = 72.6 with speed of wave c = 2.9 x 10^8 m/s for scope photo measurements.

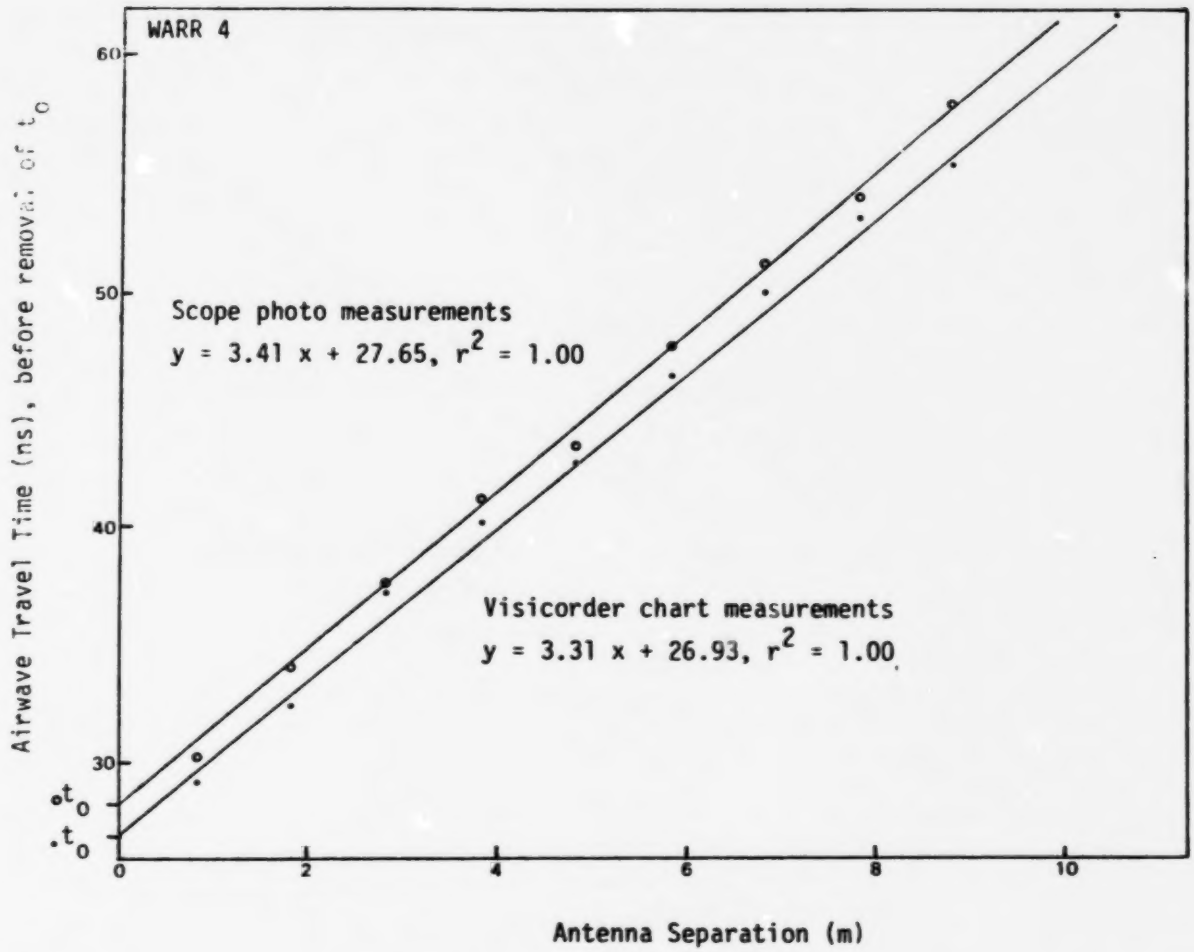


FIGURE C.3 - GRAPH OF AIRWAVE TRAVEL TIME VERSUS ANTENNA SEPATATION - Linear regression yields t_o = 26.9 ns with speed of wave c = 3.0×10^8 m/s for visicorder chart measurements, and t_o = 27.7 ns with speed of wave c = 2.9×10^8 m/s for scope photo measurements.

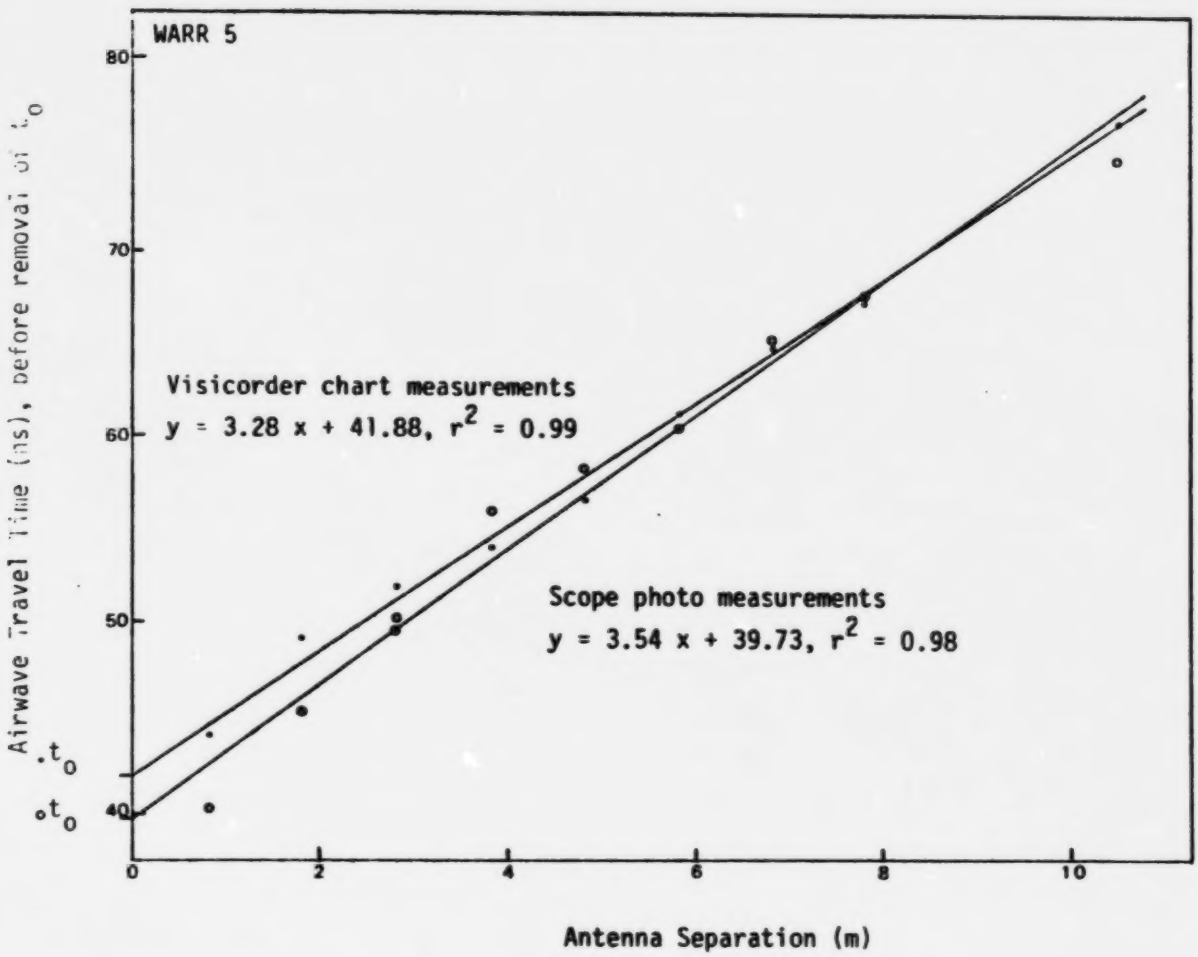


FIGURE C.4 - GRAPH OF AIRWAVE TRAVEL TIME VERSUS ANTENNA SEPARATION - Linear regression yields t_o = 41.9 ns with speed of wave c = 3.0 x 10^8 m/s for visicorder chart measurements, and t_o 39.7 ns with speed of wave c = 2.8 x 10^8 m/s for scope photo measurements.

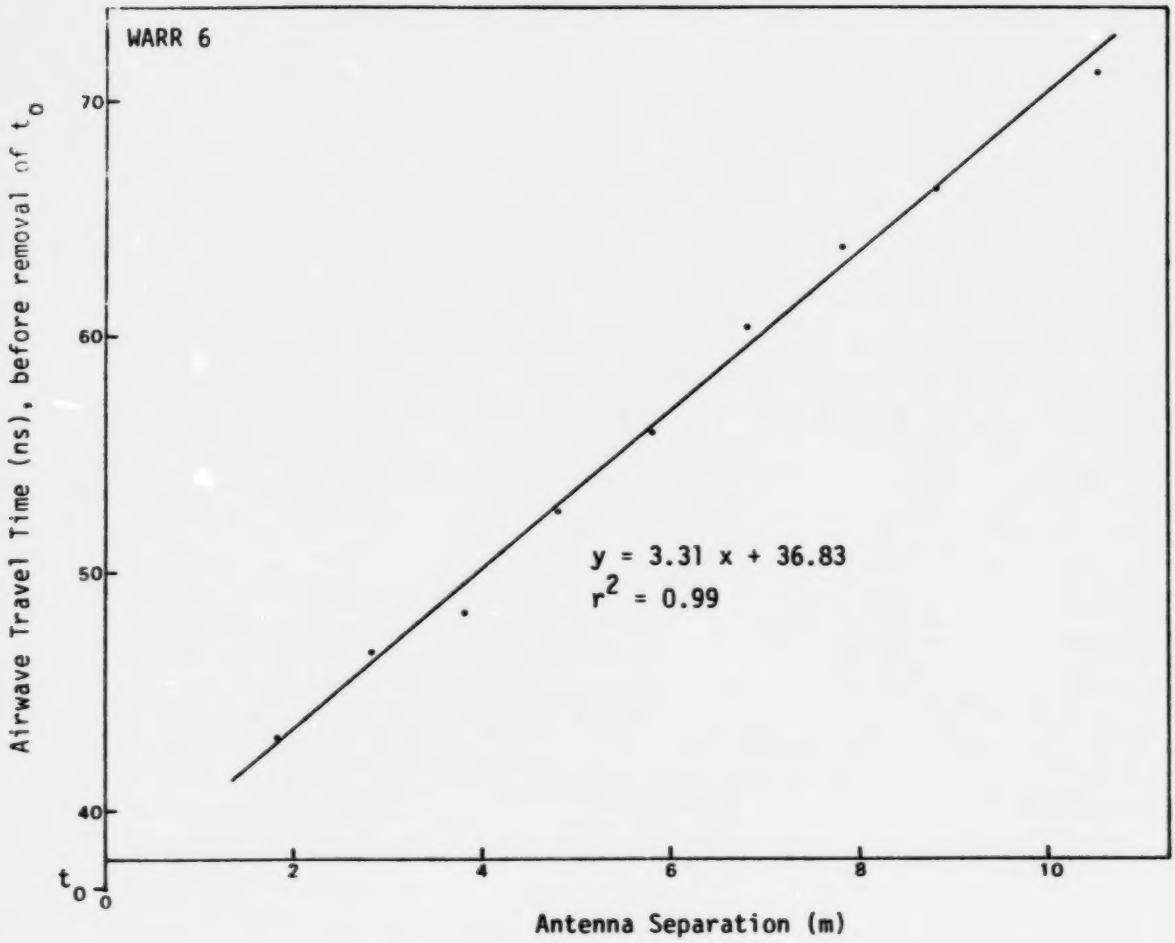


FIGURE C.5 - GRAPH OF AIRWAVE TRAVEL TIME VERSUS ANTENNA SEPARATION - Linear regression yields t_o = 36.8 ns and speed of wave c = 3.0 x 10^8 m/s.

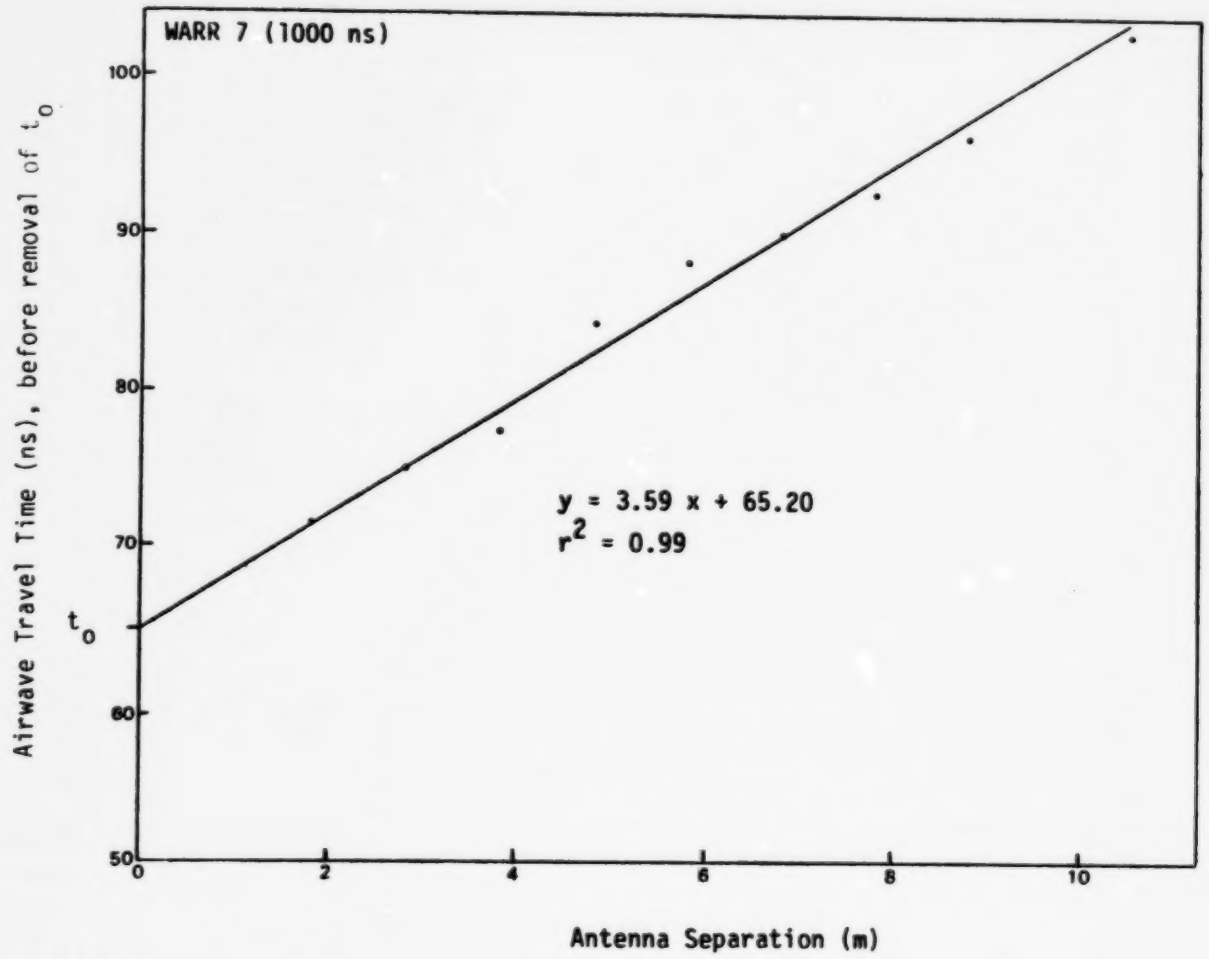


FIGURE C.6 -GRAPH OF AIRWAVE TRAVEL TIME VERSUS ANTENNA SEPARATION - Linear regression yields t_o = 65.2 ns and speed of wave c = 2.8×10^8 m/s.

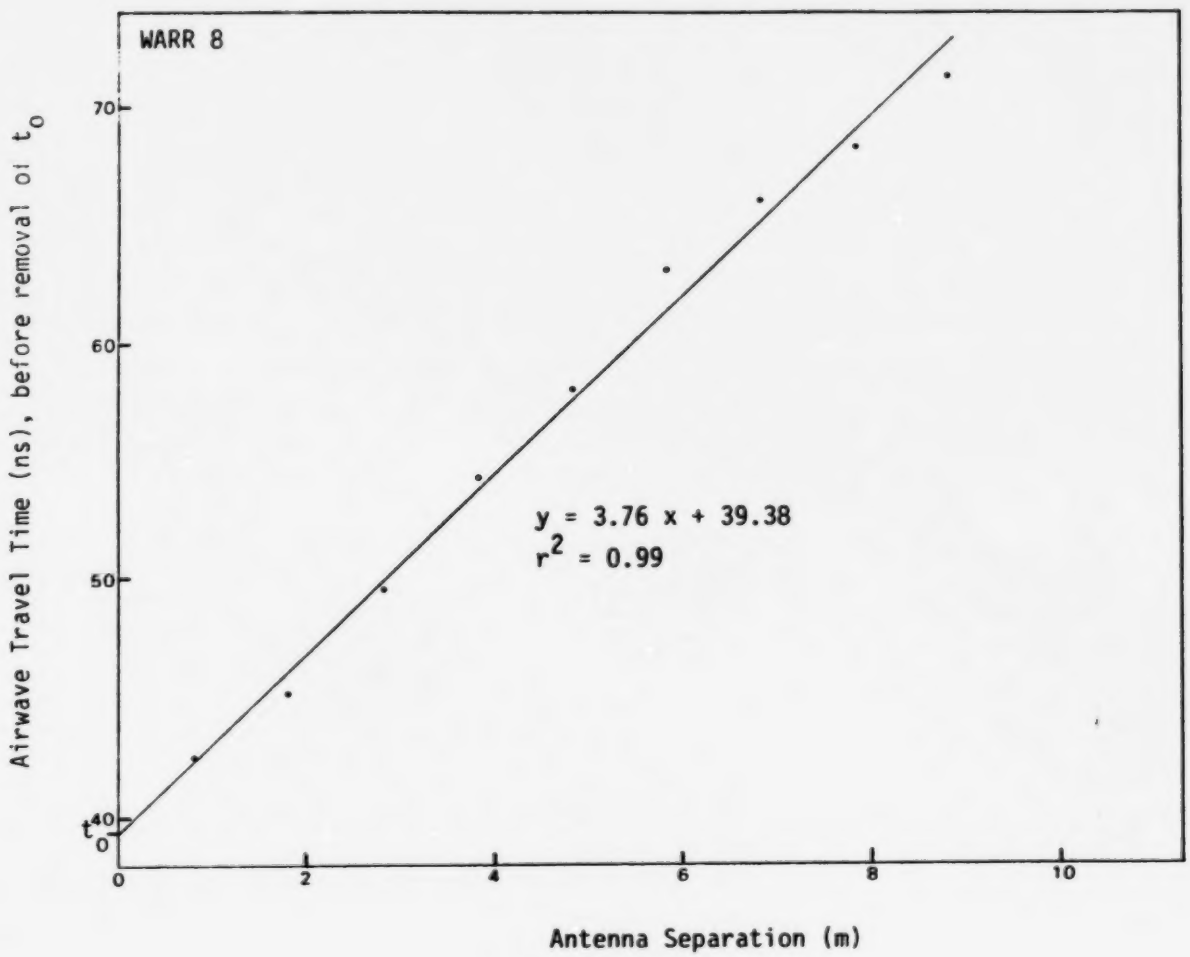


FIGURE C.7 - GRAPH OF AIRWAVE TRAVEL TIME VERSUS ANTENNA SEPARATION - Linear regression yields t_o = 39.4 ns and speed of wave c = 2.7 x 10^8 m/s.

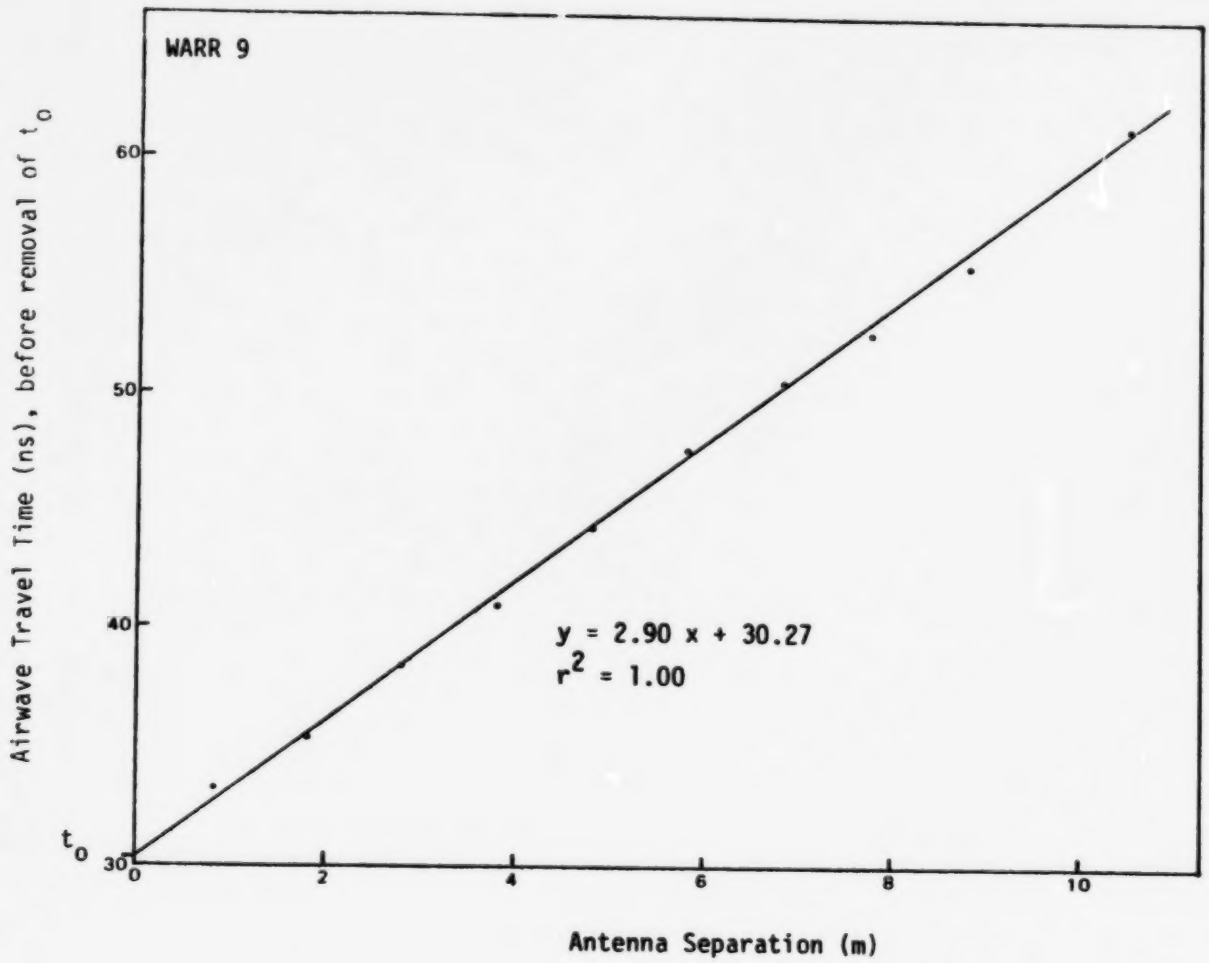


FIGURE C.8- GRAPH OF AIRWAVE TRAVEL TIME VERSUS ANTENNA SEPARATION - Linear regression yields t_o = 30.3 ns and speed of wave c = 3.4 x 10^8 m/s.

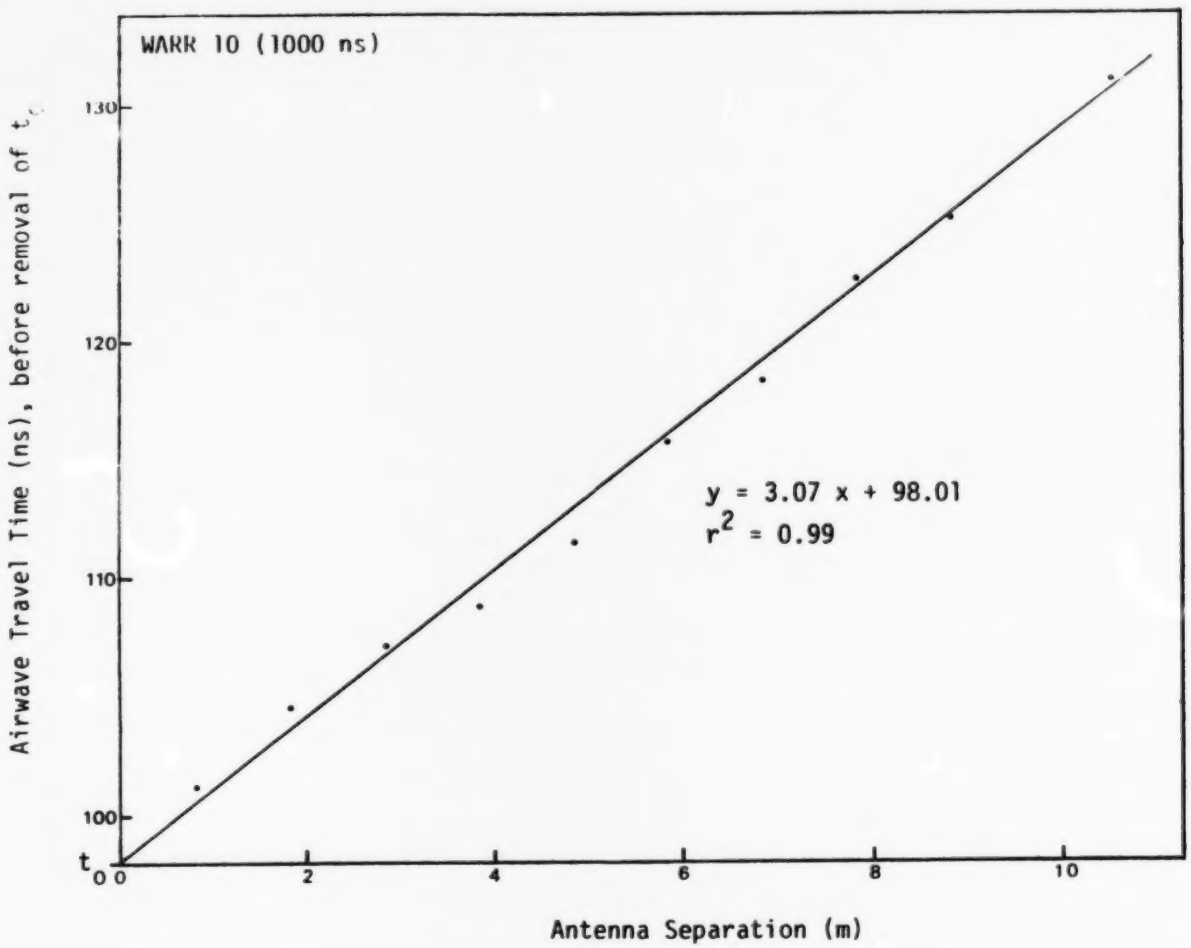


FIGURE C.9 - GRAPH OF AIRWAVE TRAVEL TIME VERSUS ANTENNA SEPARATION - Linear regression yields t_o = 98.0 ns and speed of wave c = 3.3 x 10^8 m/s.

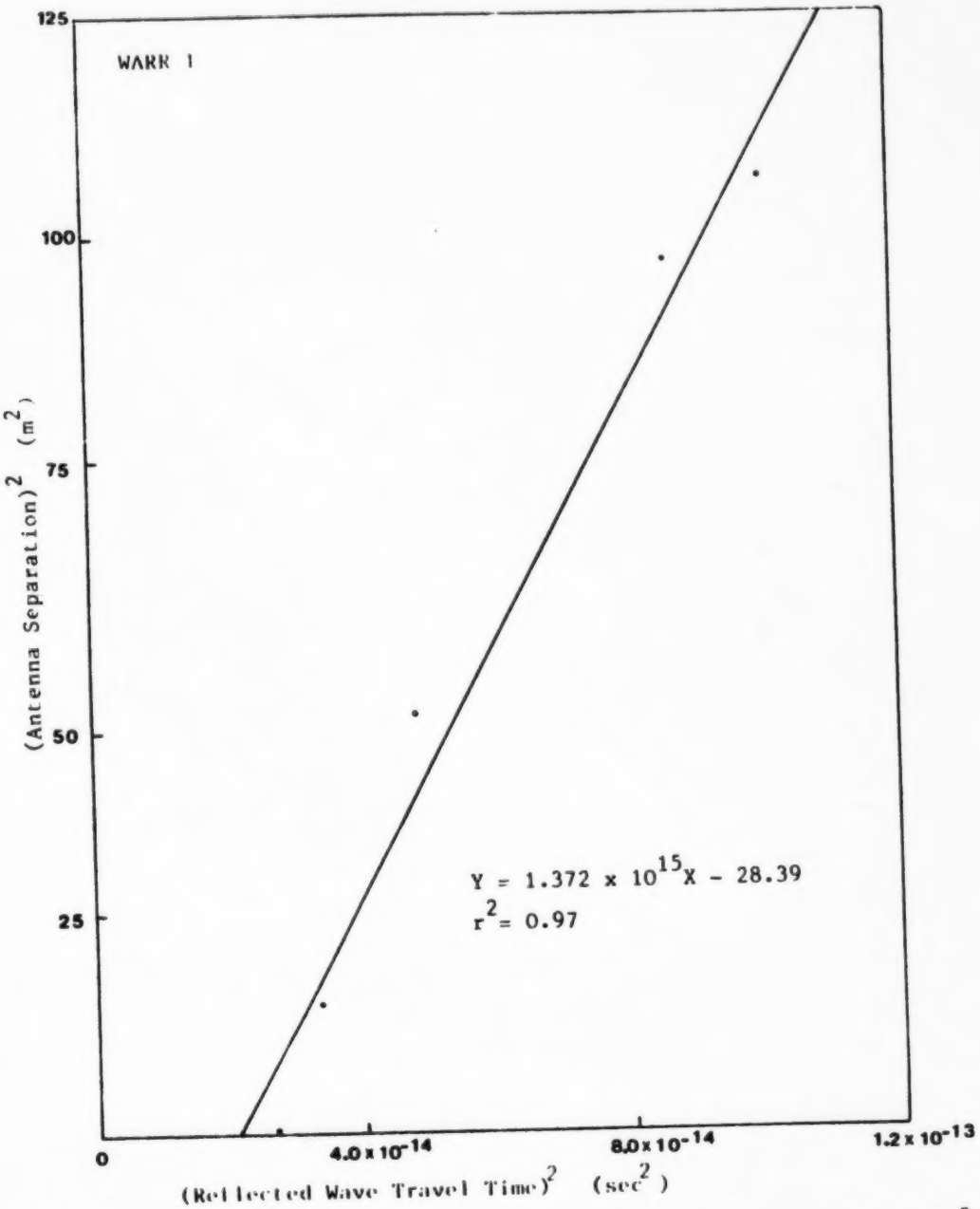


FIGURE C.10 - GRAPH OF (ANTENNA SEPARATION)^2 VERSUS (REFLECTED WAVE TRAVEL TIME)^2

From the slope of the straight line fit to the data, the dielectric constant = 65.6 and the propagation velocity = 0.037 m/ns. From the intercept, the depth at the WARR site = 2.66 m

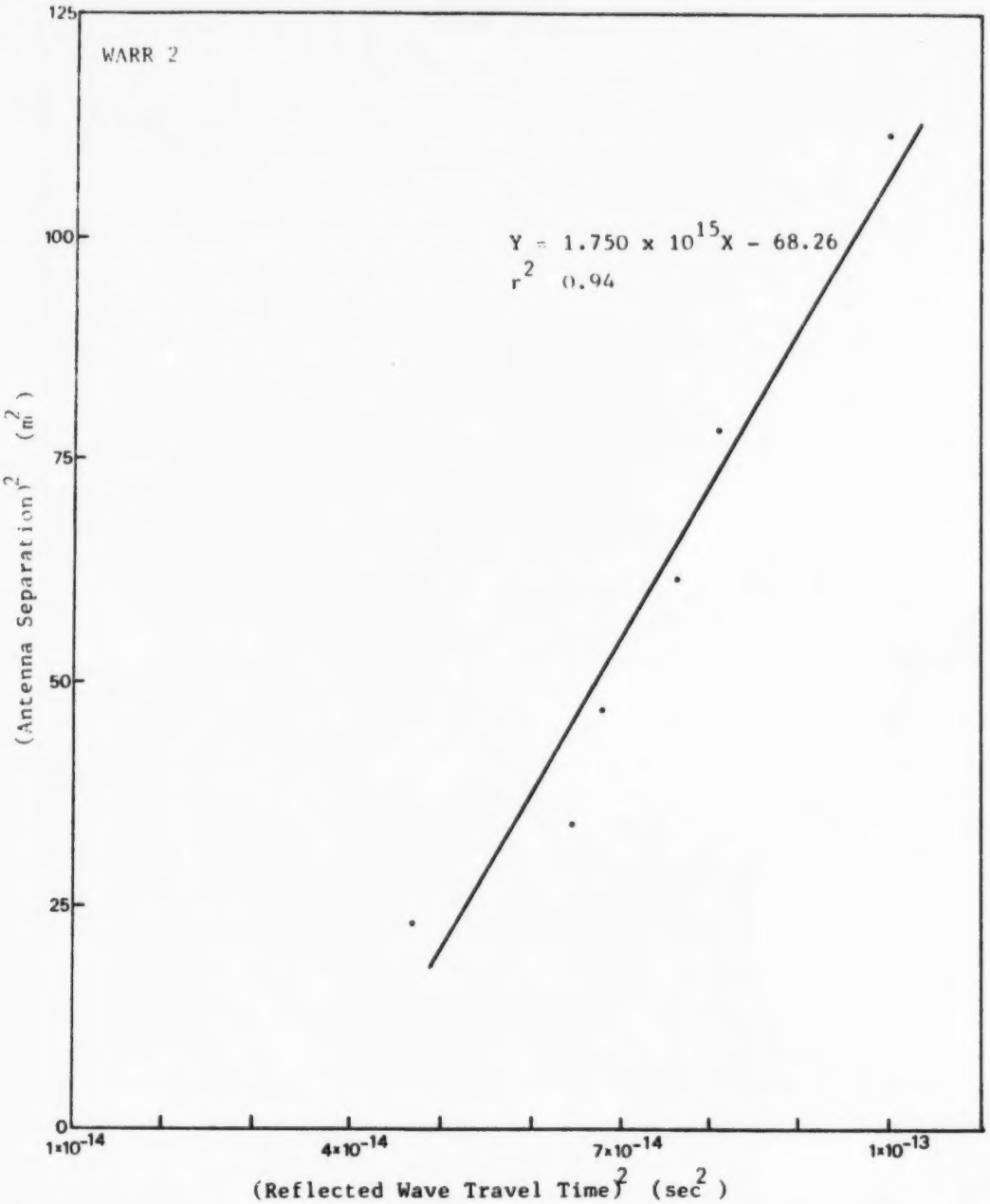


FIGURE C.11 - GRAPH OF (ANTENNA SEPERATION)^2 VERSUS (REFLECTED WAVE TRAVEL TIME)^2

From the slope of the straight line fit to the data, the dielectric constant = 51.4 and the propagation velocity = 0.042 m/ns. From the intercept, the depth at the WARR site = 4.13m

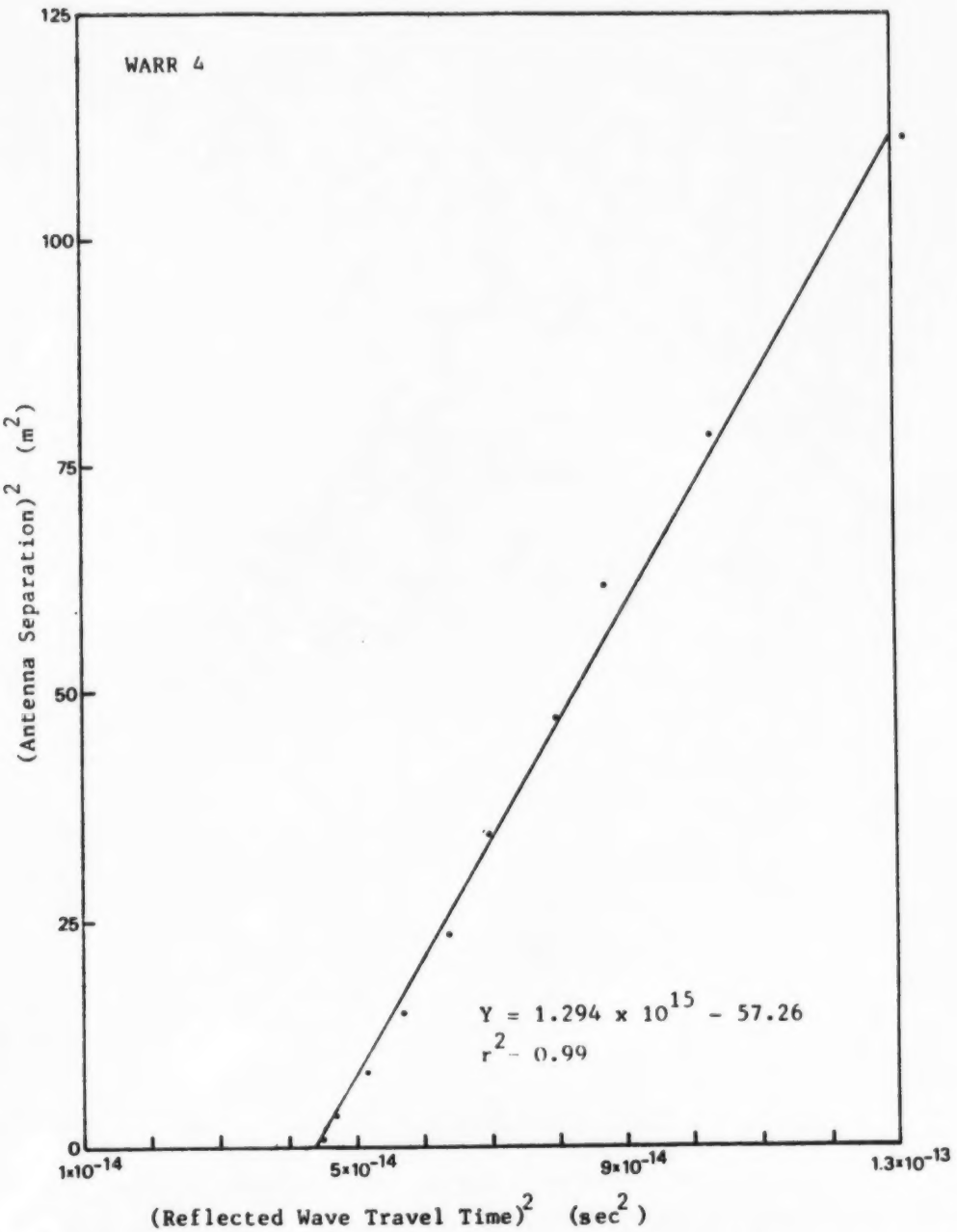


FIGURE C.12 - GRAPH OF (ANTENNA SEPARATION)^2 VERSUS (REFLECTED WAVE TRAVEL TIME)^2

From the slope of the straight line fit to the data, the dielectric constant = 69.5 and the propagation velocity = 0.036 m/ns. From the intercept, the depth at the WARR site = 3.78 m

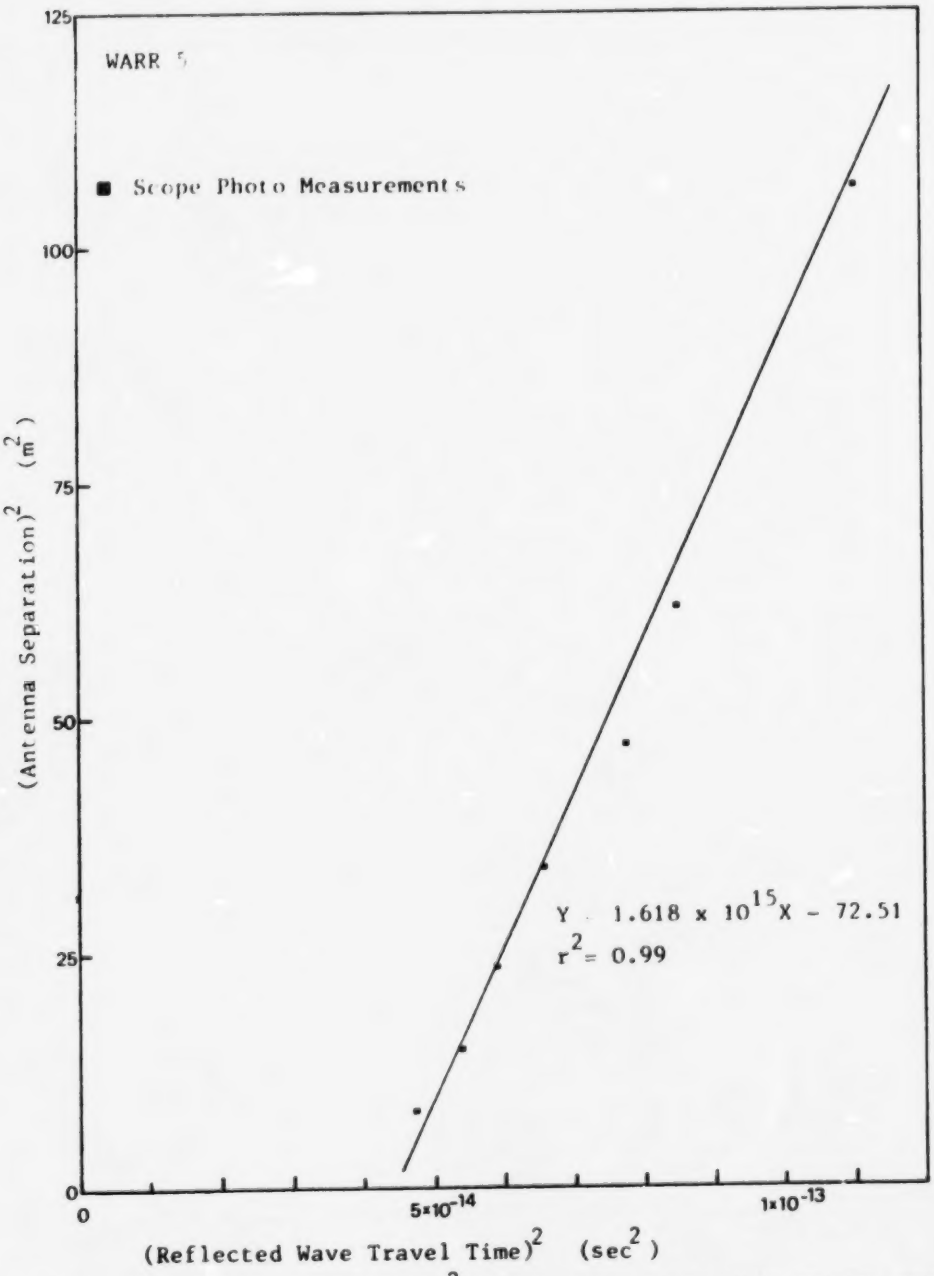


FIGURE C.13 - GRAPH OF (ANTENNA SEPARATION)^2 VERSUS (REFLECTED WAVE TRAVEL TIME)^2

From the slope of the straight line fit to the data, the dielectric constant = 55.6 and the propagation velocity = 0.040 m/ns. From the intercept the depth at the WARR site = 4.26 m

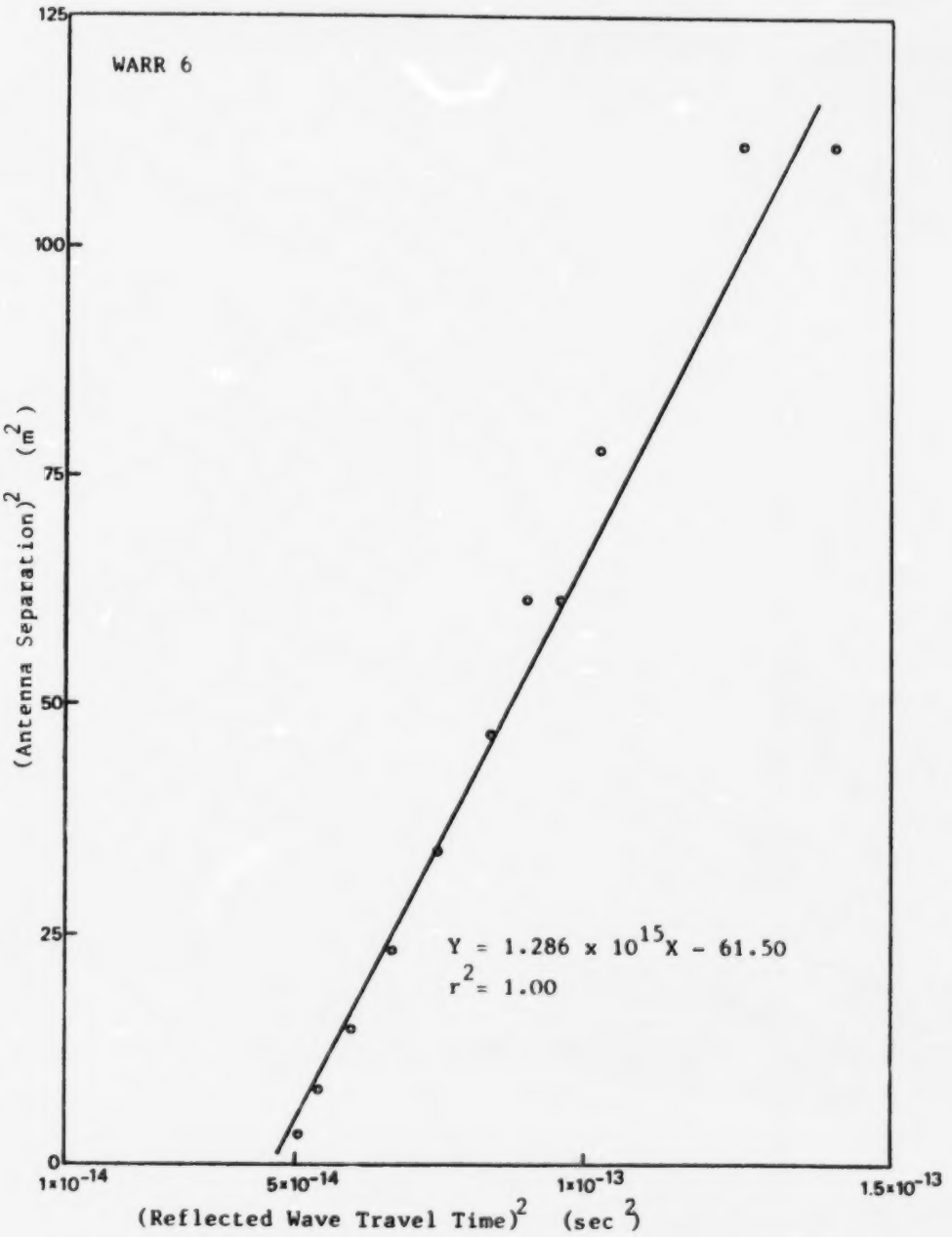


FIGURE C.14 - GRAPH OF (ANTENNA SEPARATION)^2 VERSUS (REFLECTED WAVE TRAVEL TIME)^2

From the slope of the straight line fit to the data, the dielectric constant 70.0 and the propagation velocity = 0.036 m/ns. From the intercept, the depth at the WARR site = 3.92 m.

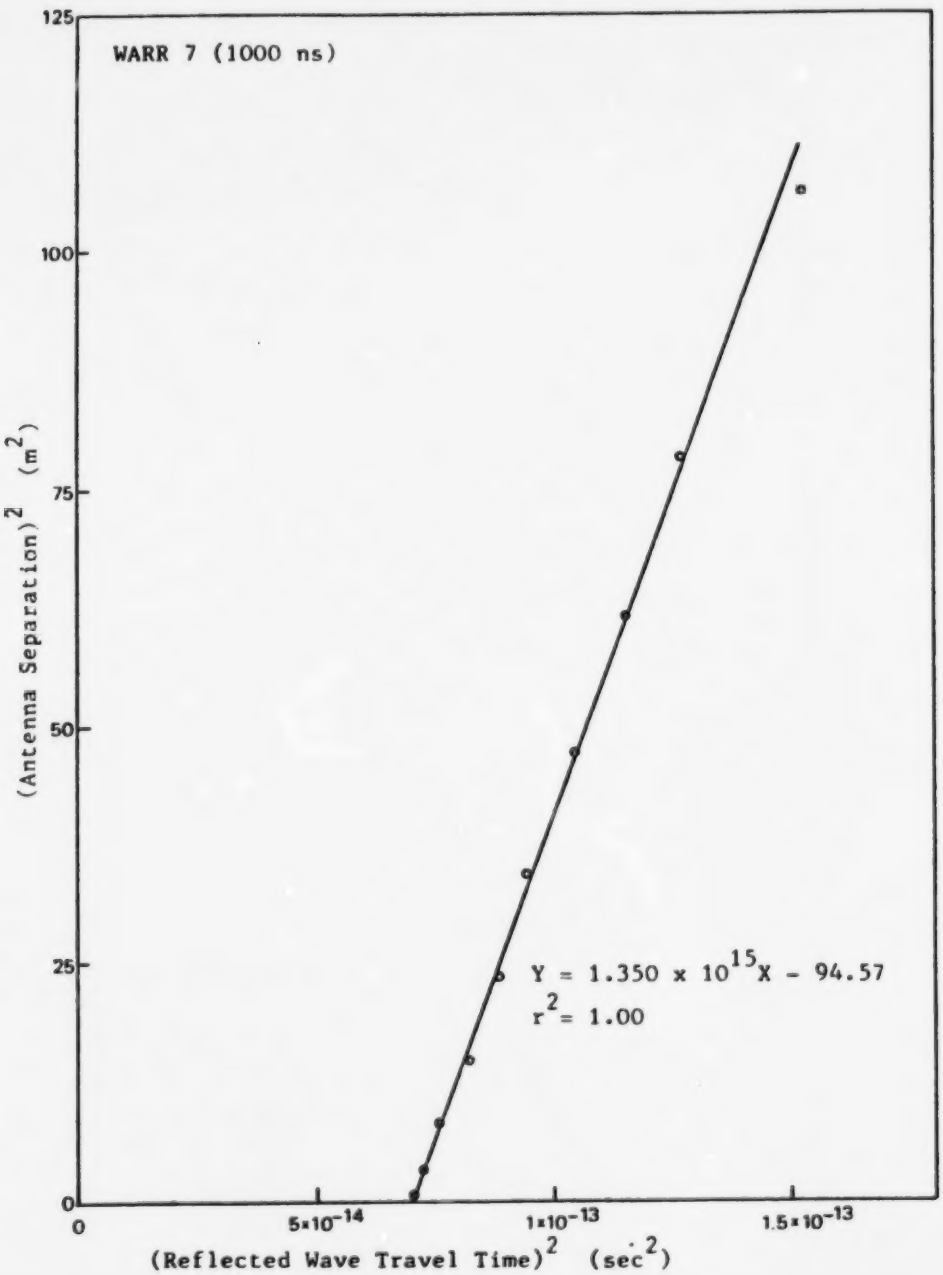


FIGURE C.15- GRAPH OF (ANTENNA SEPARATION)^2 VERSUS (REFLECTED WAVE TRAVEL TIME)^2

From the slope of the straight line fit to the data, the dielectric constant = 66.7 and propagation velocity = 0.037 m/ns. From the intercept, the depth at the WARR site = 4.86 m

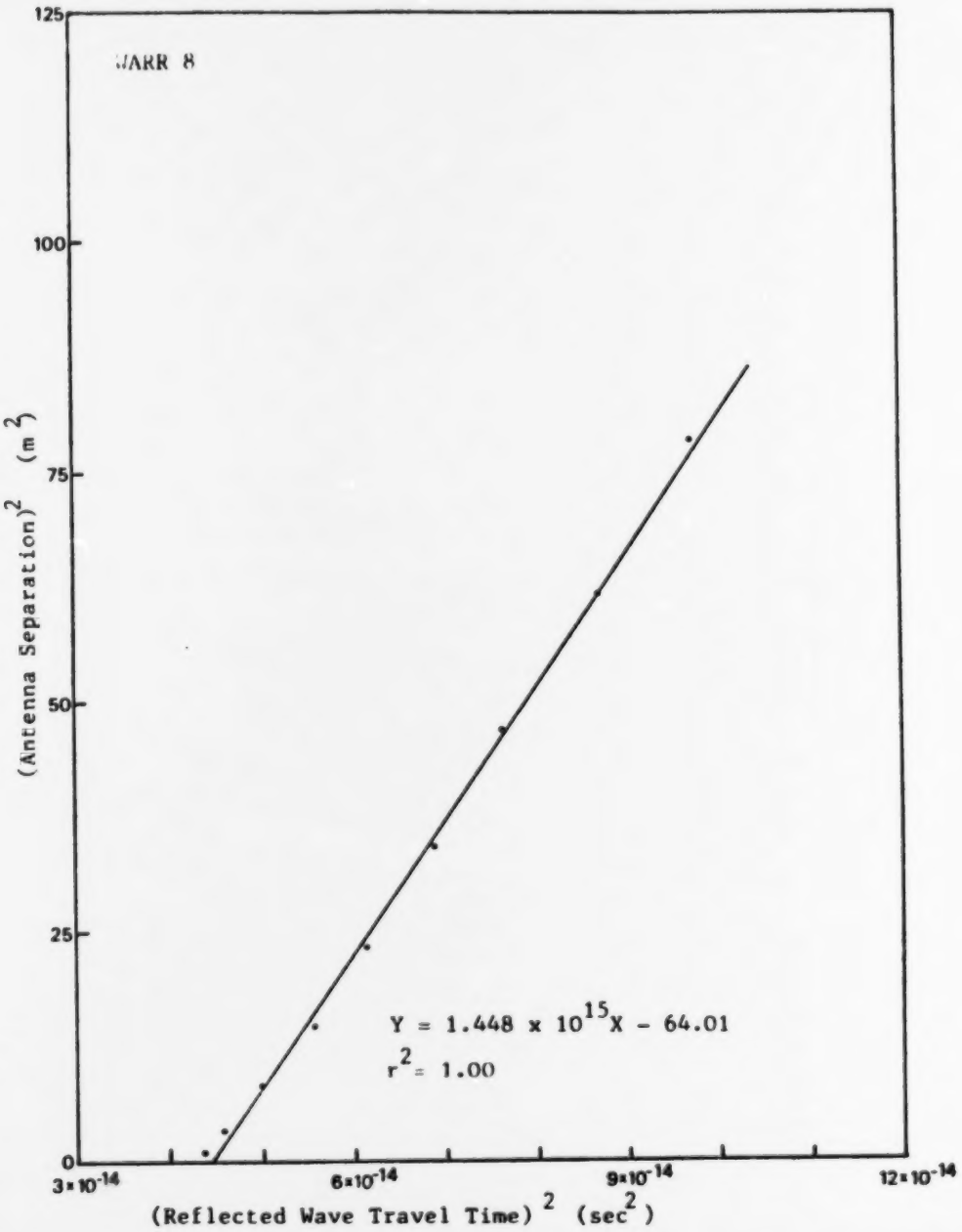


FIGURE C.16 - GRAPH OF (ANTENNA SEPARATION)^2 VERSUS (REFLECTED WAVE TRAVEL TIME)^2

From the slope of the straight line fit to the data, the dielectric constant = 62.2 and the propagation velocity = 0.038 m/ns. From the intercept, the depth at the WARR site = 4.00 m

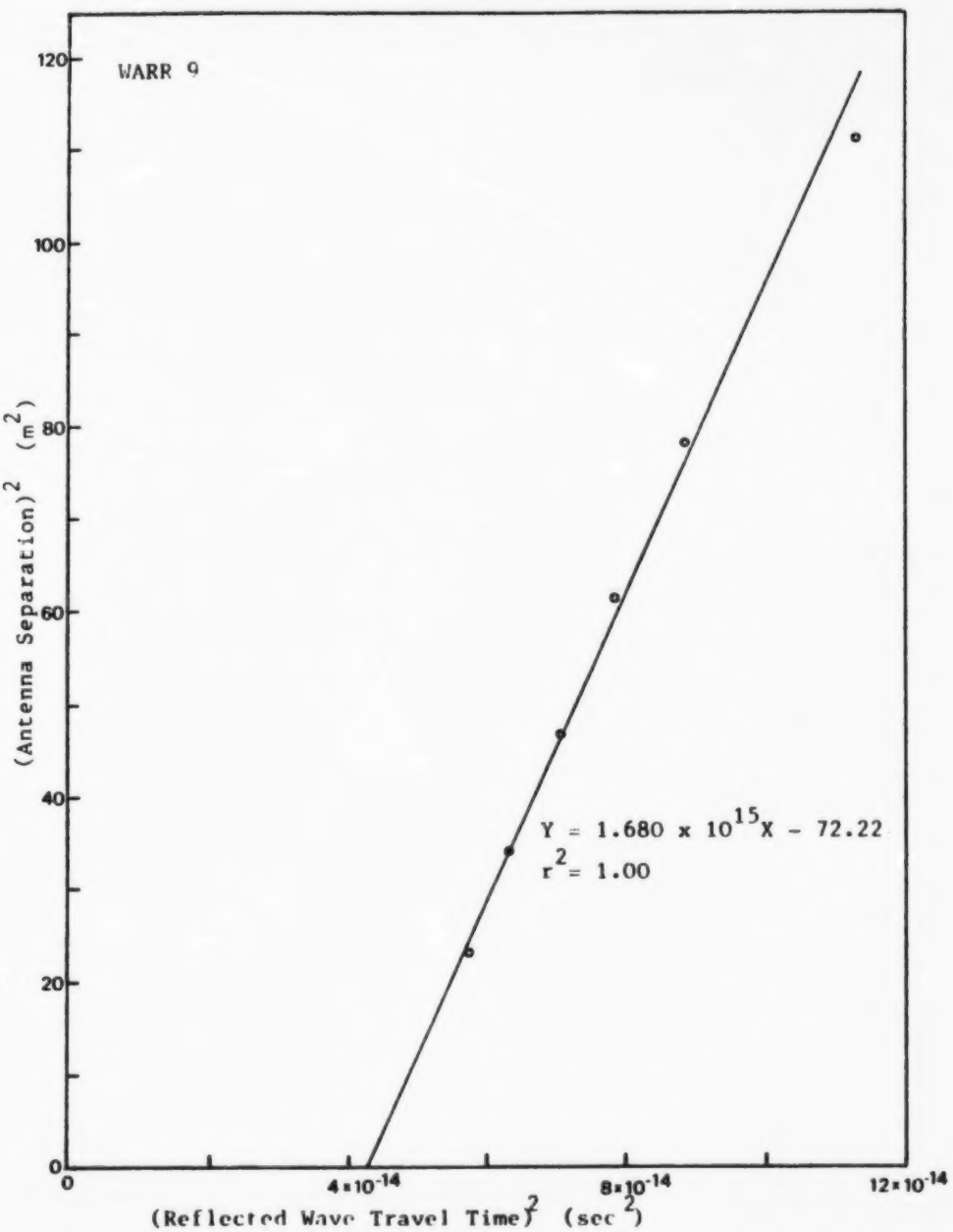


FIGURE C.17 - GRAPH OF (ANTENNA SEPARATION)^2 VERSUS (REFLECTED WAVE TRAVEL TIME)^2

From the slope of the straight line fit to the data, the dielectric constant = 53.6 and the propagation velocity = 0.041 m/ns. From the intercept, the depth at the WARR site = 4.25 m

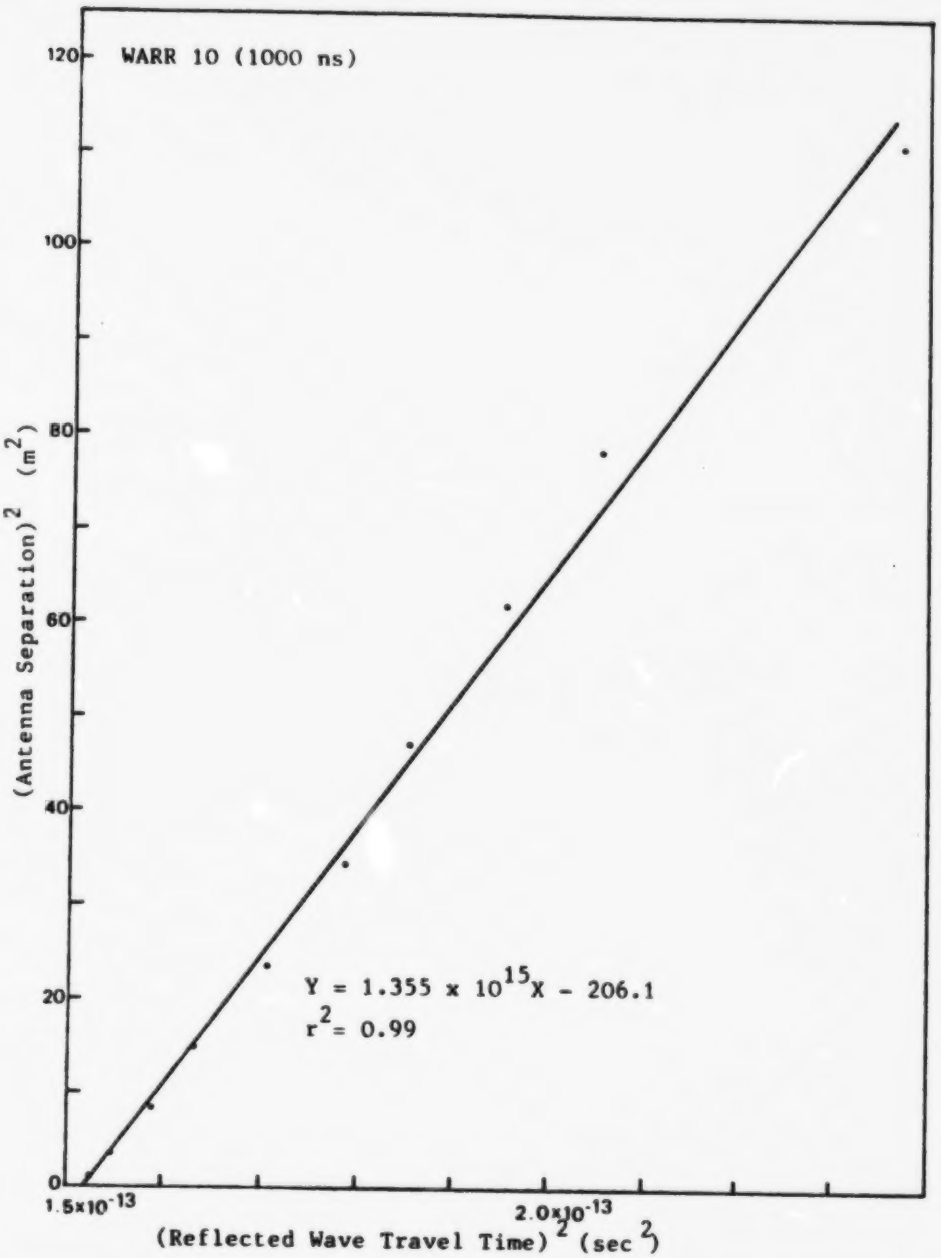


FIGURE C.18 - GRAPH OF (ANTENNA SEPARATION)^2 VERSUS (REFLECTED WAVE TRAVEL TIME)^2

From the slope of the straight line fit to the data, the dielectric constant = 66.4 and the propagation velocity = 0.037 m/ns. From the intercept, the depth at the WARR site = 7.18 m

APPENDIX D

GROUND TRUTH DEPTH VERSUS MEASURED TIME DELAY GRAPHS
FOR INDIVIDUAL DEPOSITS

REMOTEC
Remotec Applications Inc.

Remotec Applications Inc.,
Mailing Address: P.O. Box 5547,
St. John's, Newfoundland,
Canada, A1C 5W4

Business Address: K-Mart Plaza,
Topsail Road, Suite 202
Telephone (709) 364-1779, -2032,
-2033
Telex 016-4939

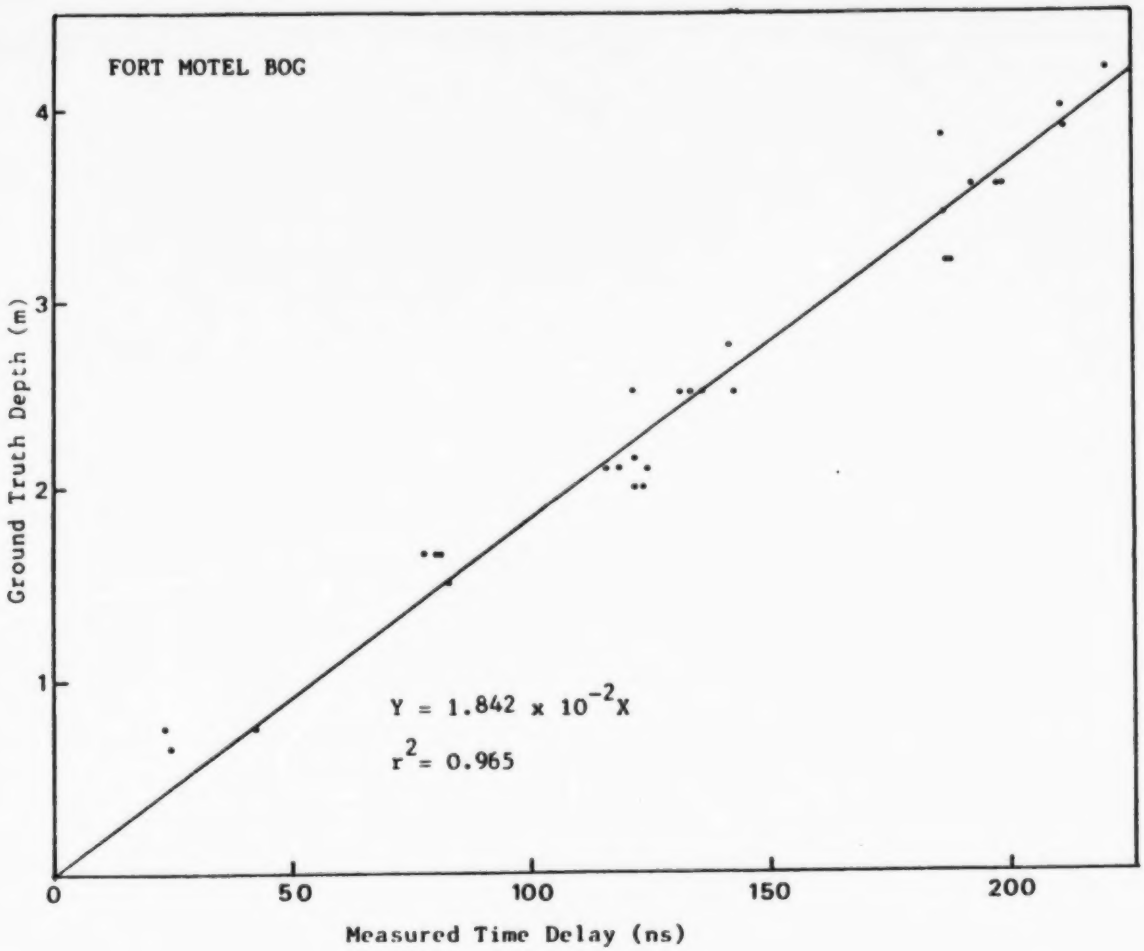


FIGURE D.1 - GRAPH OF GROUND TRUTH DEPTH VERSUS MEASURED TIME DELAY

From the slope of the straight line through the origin, the dielectric constant = 66.3 and the propagation velocity = 0.037 m/ns

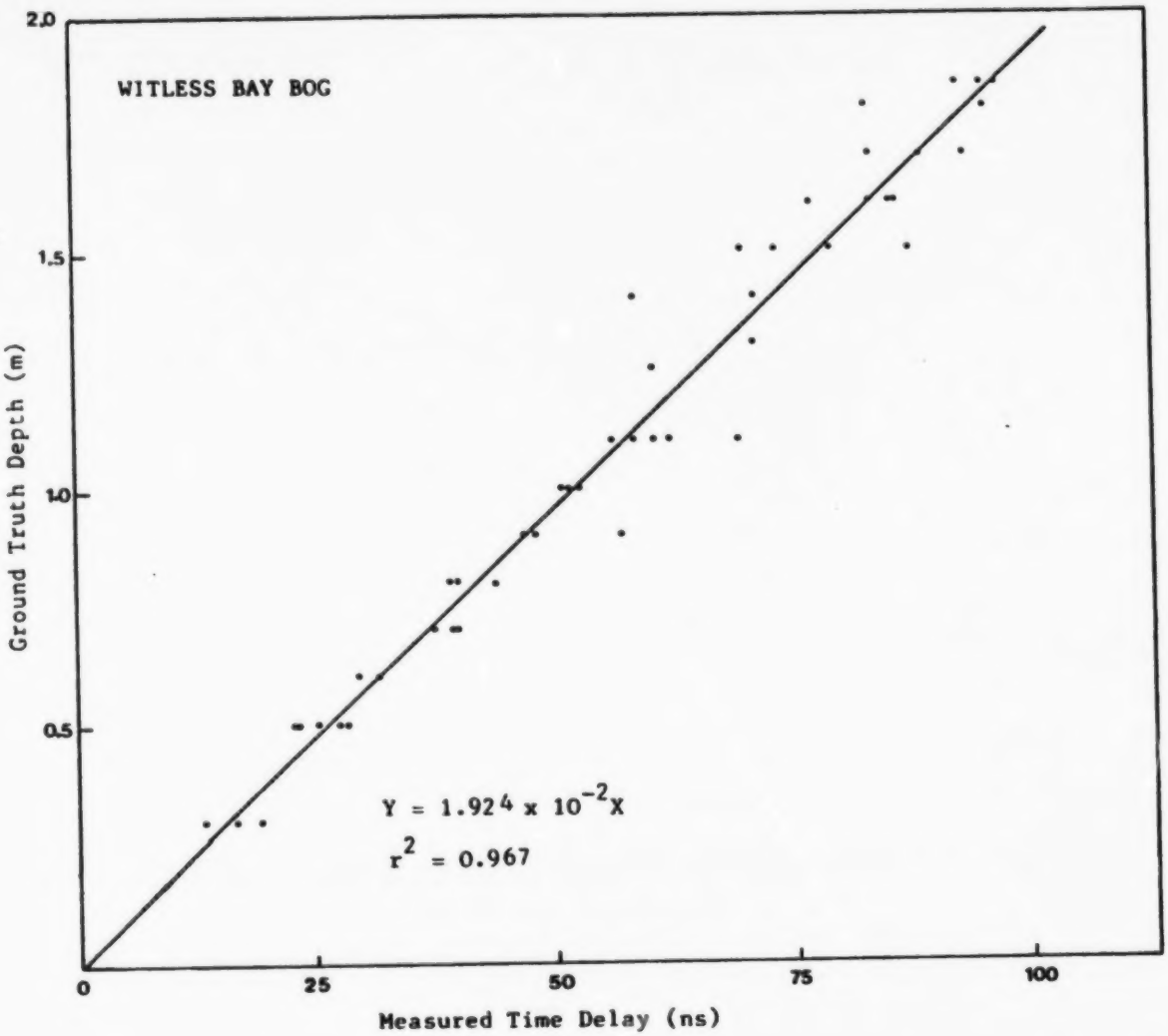


FIGURE D.2 - GRAPH OF GROUND TRUTH DEPTH VERSUS MEASURED TIME DELAY

From the slope of the straight line through the origin, the dielectric constant = 60.8 and the propagation velocity = 0.038 m/ns

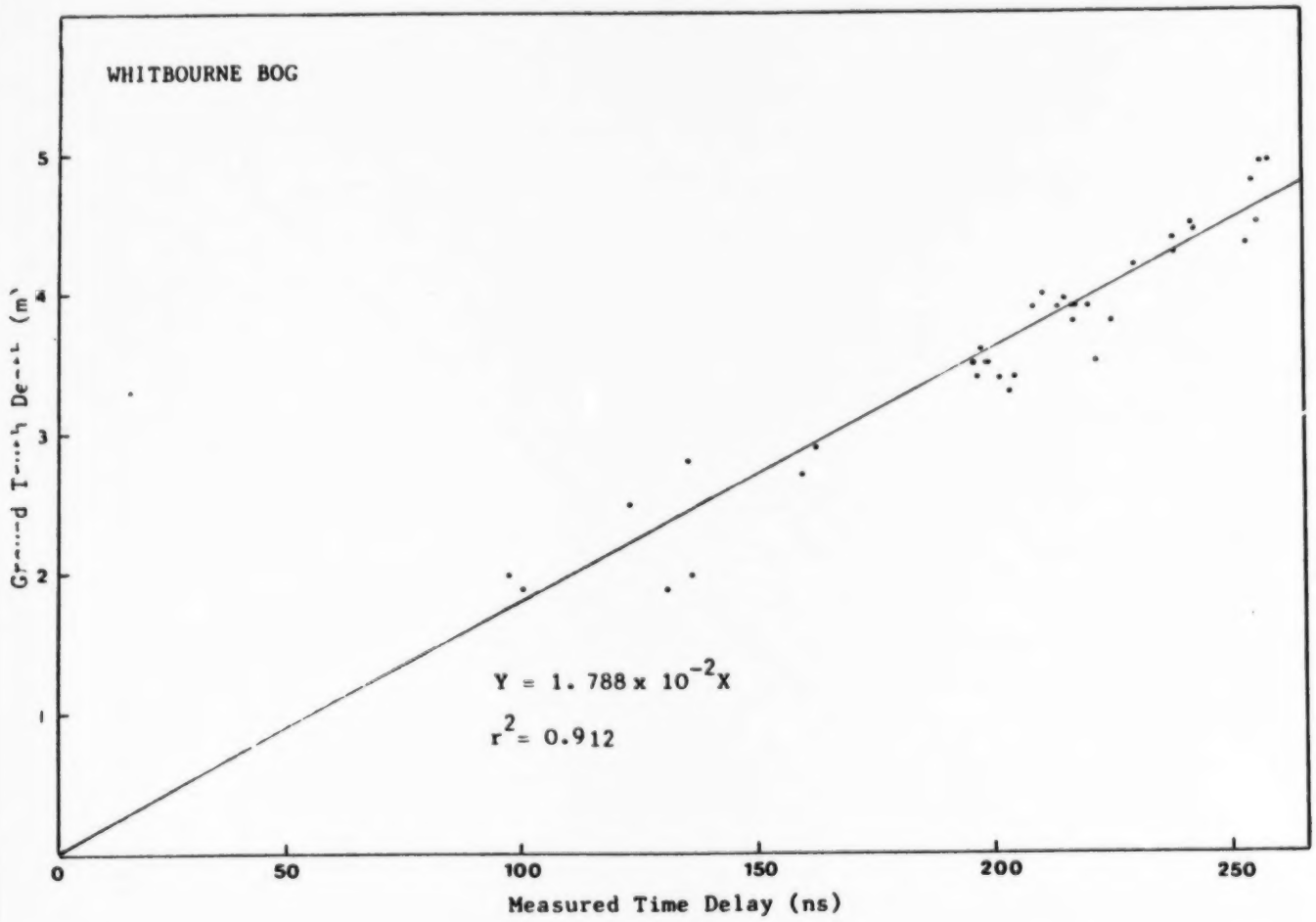


FIGURE D.3 - GRAPH OF GROUND TRUTH DEPTH VERSUS MEASURED TIME DELAY

From the slope of the straight line through the origin, the dielectric constant = 70.4 and the propagation velocity = 0.036 m/ns

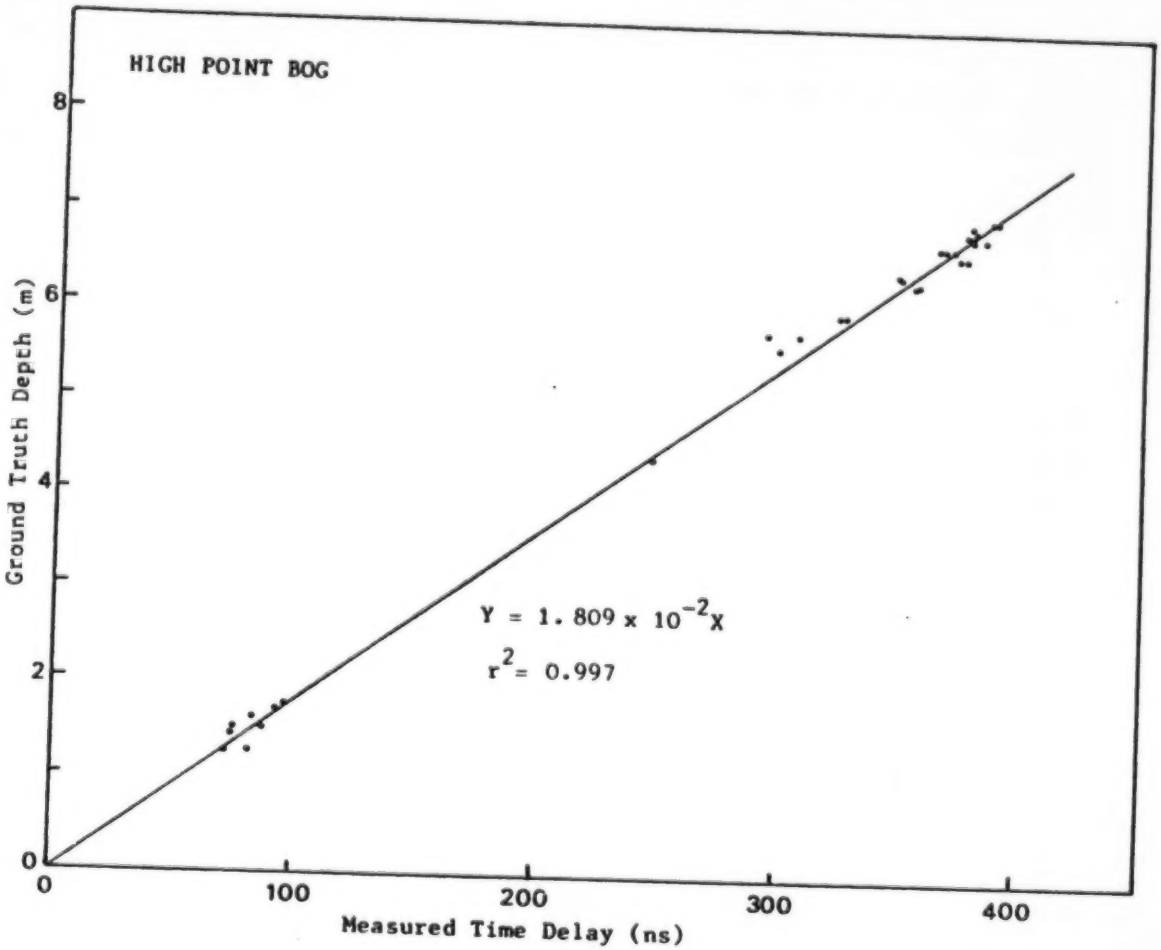


FIGURE D.4 - GRAPH OF GROUND TRUTH DEPTH VERSUS MEASURED TIME DELAY

From the slope of the straight line through the origin, the dielectric constant = 68.8 and the propagation veloocity = 0.036 m/ns

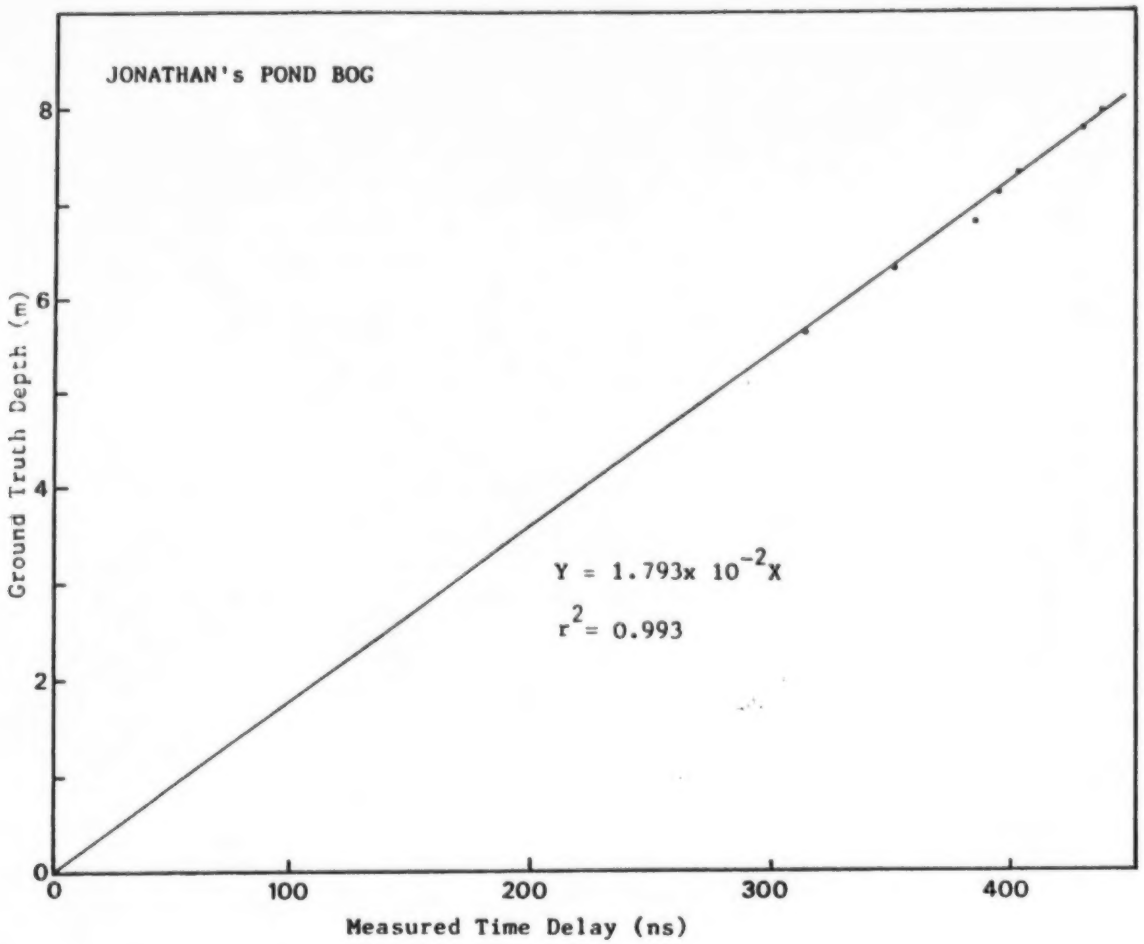


FIGURE D.5 - GRAPH OF GROUND TRUTH DEPTH VERSUS MEASURED TIME DELAY

From the slope of the straight line through the origin, the dielectric constant = 70 . 0 and the propagation velocity = 0.036 m/ns

POOR

QUALITY

ORIGINAL